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TP 10821E

EVALUATION OF SELECTED PORTABLE WEIGH SCALES FOR DETECTION OF OVERLOADED AIRCRAFT

Prepared for

Transportation Development Centre
Policy and Coordination Group
Transport Canada

By

Romi Singh and Andreas Hoppe
Aviation Planning Services Ltd.

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February 1991

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The contents of this report reflect the views of the authors and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus.

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16. Abstract

The objective of this study was to determine the availability of portable weighing equipment to meet Transport Canada performance requirements for use in the detection of overloaded aircraft for regulation enforcement purposes. If not available, the study was to recommend the most suitable technology for further research and development to achieve performance compliance.

After comparison of the current products with the performance requirements, the latter were revised to allow three current products, manufactured by Haenni, Pat Equipment and Intercomp, to qualify. These three products were tested in field trials under controlled conditions. The scale manufactured by Haenni was identified as the most suitable, satisfying all but one element of the specified performance requirements (system weight).Two areas of research and development were pursued for enhancing detection performance involving wind compensation and centre of gravity calculation. The study further developed an approach for detection of overloaded float planes and verified its applicability through field trials.

Due to the limited data base, it is recommended that a controlled weighing program be initially introduced to enhance the data base and permit the definition of any further testing and/or procedures development that may be required.

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16. Résumé

Le but de cette recherche était de déterminer s'il se trouve sur le marché une bascule de pesage portable pouvant satisfaire aux spécifications de performances établies par Transports Canada en matière de détection des aéronefs en surcharge. Dans le cas contraire, elle devait sélectionner la technologie qui, par des recherches et un développement ultérieur, serait le plus susceptible de répondre aux exigences.

Après une évaluation des performances des matériels sur le marché, les critères de sélection ont été modifiés de manière à permettre à trois produits, fabriqués par Haenni, Pat Equipment et Intercomp, respectivement, de se qualifier. Ces trois bascules ont été soumises à des essais sur le terrain dans des conditions contrôlées. La bascule fabriquée par Haenni a satisfait à tous les critères prévus sauf un, celui du poids. Des travaux de recherche et de développement ont été réalisés en vue de doter la bascule d'un outil de calcul du centre de gravité (c.g.) et de compensation de l'effet du vent. La recherche s'est également étendue à la détection des avions à flotteurs en surcharge, et a vérifié l'applicabilité du principe en jeu par des essais sur le terrain.

Afin d'enrichir la base de données existante, il est recommandé de lancer un programme de pesages contrôlés destiné à permettre la définition des essais complémentaires et (ou) procédures nouvelles susceptibles de mener à une méthode de pesage qui aura reçu une validation pleine et entière.

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The following are to be thanked for their assistance in providing information for this study: Mr. Manzur Hug (Enforcement and Legislation Branch, Transport Canada); Messrs. Serge Beauchamp and Bernard Henri (Quebec Region, Transport Canada); Mr. D. Routhier (Regional Superintendent, Ontario Region, Transport Canada); Mr. G. Tremblay (Quebec Region, Transport Canada); and Mr. Lefrançois (Police Lieutenant, City of Gatineau Police Department).

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PART 3 - "Wind Effects and Seaplane Detection", report dated August 1990

SUMMARY

1. **INTRODUCTION**

The Transportation Development Centre (TDC) contracted Aviation Planning Services Ltd. (APS) in 1988 to determine the availability of portable weighing equipment that satisfied Transport Canada (TC) performance specifications, for the detection of overloaded aircraft. The specifications were originally developed by the Enforcement and Legislation Branch of TC's Aviation Group (TCAG).

The initial study, concluded in February 1989, identified the available equipment and the deficiencies in the related usage data. In a second study in 1990, the usage data deficiencies were addressed through field experiments. This second study also addressed practical problems related to the measurement of aircraft weights in the field and quantified the effect of wind on the measured weight of an aircraft. Procedures to determine the gross weights of float planes or seaplanes were also developed.

This document is a summary of the work performed and its results. It presents the evolution of the specifications, results of the research, conclusions, and recommendations for work required to place practical and reliable tools in the hands of TCAG officers, who must defensibly conduct the weighings of potentially overloaded aircraft in the field.

The complete results of the study are presented in three separate reports, which are included in full at the end of this summary:

PART 1 - "Specifications and Equipment Evaluation", February 1989

PART 2 - "Scale Testing and Centre of Gravity Compensation", May 1990

PART 3 - "Wind Effects and Seaplane Detection", August 1990

2. PART 1: SPECIFICATIONS AND EQUIPMENT EVALUATION

2.1 Specifications

The 1988 study (Part 1) began by seeking consensus on the specifications and comparative criteria. These consisted of:

- Wheel pad size (volumetric space)
- Weight of system
- System capacity (maximum measurable weight limitations)
- Operating temperature range
- Wheel pad thickness (height of pad)
- Maintainability and reliability
- Wind compensation
- Liability and risk related to manipulating or jacking up of expensive aircraft

The original specifications required the equipment to have a wheel pad maximum size of 61 cm x 76 cm, maximum weight of 23 kg, capacity of 90 720 kg, an operating temperature range of -30°C to +35°C, a maximum pad thickness of 2.54 cm and a wind model to allow weighings during wind conditions.

The products available at the time of the study did not meet the TCAG specifications. Therefore, some of the constraints were relaxed. Maximum pad size constraint was redefined to be 61 cm x 102 cm, maximum weight was defined as 91 kg, capacity upper bound was set at 29 484 kg, and the lower operating temperature limit was redefined as -10°C.

While in the original specifications a wind compensation model was required, in the relaxed constraints, TCAG established that a wind limitation was acceptable, such that the weighing would not be undertaken in winds exceeding this limit.

The initial and revised TCAG specifications are included in Table 1. In this Table, the selection criteria and their relative rankings, as well as the scores of the three scales are summarised. The scale performance values are indicated and can easily be compared with the TCAG performance specifications. The scores refer to the results of the binary decision analysis described in Parts 1 and 2 of this report. Note that Haenni scales are consistently ranked the best, with an overall score of 37.5% in Part 1 and 41.7% in Part 2.

TABLE 1
SUMMARY OF PERFORMANCE SPECIFICATIONS AND CANDIDATE SCALE CHARACTERISTICS

CRITERIA	TRANSPORT CANADA PERFORMANCE SPECIFICATIONS		CRITERIA WEIGHTING		EQUIPMENT MANUFACTURERS								
					HAENNI			PAT EQUIPMENT			INTERCOMP		
	INITIAL	REVISED	PART 1*	PART 2*	PERFORMANCE VALUES	SCORES PART 1	SCORES PART 2	PERFORMANCE VALUES	SCORES PART 1	SCORES PART 2	PERFORMANCE VALUES	SCORES PART 1	SCORES PART 2
PAD SIZE (cm x cm) (WEIGHING SURFACE)	61 x 76	61 x 102	17.9%	3.6%	36 x66	6	2	38 x 56	3	1	38 x 57	9	1
PAD THICKNESS (cm)	MAX 2.54 cm	Approx 2.54 cm	21.4%	25.0%	2	11	13	3.0	7	8	4.3	4	4
SYSTEM WEIGHT (kg)	23	91	14.3%	17.9%	50 (14.5/Pad)	2	9	76 (22.5/Pad)	6	5	70 (21.7/Pad)	6	5
MAINTAINABILITY / RELIABILITY	QUALITATIVE	QUALITATIVE	25.0%	14.3%	-	10	2	-	10	7	-	4	5
SYSTEM CAPACITY (kg) (With 3 Pads)	90,720	29,484	10.7%	N/A	30,000	4	N/A	30,000	4	N/A	30,000	2	N/A
TEMPERATURE RANGE (°C)	-35 to +35	-10 to +35	7.1%	N/A	-20 to +50	2	N/A	-10 to +40	4	N/A	-28 to +50	1	N/A
WIND COMPENSATION	DESIRED	Wind limitations Acceptable	3.6%	N/A	Wind limitations	1	N/A	Wind limitations	1	N/A	Wind limitations	1	N/A
EASE OF OPERATION	QUALITATIVE	QUALITATIVE	N/A	21.4%	-	N/A	11	-	N/A	5	-	N/A	5
ACCURACY	-	-	N/A	10.7%	-	N/A	4	-	N/A	5	-	N/A	2
SOFTWARE CAPABILITY	-	-	N/A	7.1%	-	N/A	2	-	N/A	2	-	N/A	4
TOTAL (%)			100	100		37.5	41.7		35.7	33.7		26.8	24.9

N/A = Not Applicable

SOURCE: AVIATION PLANNING SERVICES LTD. ANALYSIS

* Part 1, Part 2: Refer to values used in different phases of the work and reported respectively in Part 1 and Part 2 of this report. The different values are due to increased understanding of the equipment and the intended operations, as well as the elimination of elements in the criteria which all three scales were found to meet.

2.2 Equipment Evaluation

Approximately twenty manufacturers were canvassed to determine the availability of a suitable product. Only three produced scales which could satisfy the final set of criteria. These were scales manufactured by Haenni (which were being used at the time of the study by the Ontario and Quebec Regions of TC), PAT Equipment (used by the Ontario Ministry of Transport), and Intercomp (used by the Gatineau Police Department).

The PAT and Intercomp scales had no history of usage in aviation, while the Haenni system had mixed reviews from the Quebec and Ontario Regions. This led APS to recommend a further study, to include a series of field trials for all three systems to determine which would be the most suitable.

In addition to the need for more usage data, this part of the study also identified the need for procedures and techniques to measure the Centre of Gravity (C of G) of all aircraft, to correct for the effect of winds on the measured weight of an aircraft, and to establish the weight of waterborne seaplanes. Therefore, it was recommended that, in addition to the selection of a particular portable weighing system, further investigations should be pursued to develop a more complete set of tools for the acquisition of weight and balance data in the field.

3. PART 2: SCALE TESTING AND CENTRE OF GRAVITY COMPENSATION

Part 2 of the study involved a further refinement of the criteria for selection and field testing of the three candidate portable weighing systems under controlled

conditions to determine the optimal system for recommendation to TCAG. In addition, a model was developed for the determination of the C of G of an aircraft with respect to the nose wheel (or tailwheel) of the aircraft.

3.1 Criteria for Selection

The set of criteria presented in Table 1 against which the three candidate scales were to be measured was further refined as more experience was gained in the operation of portable weighing equipment. System capacity was eliminated as all three candidates met this criterion. Temperature range was also not tested as it was determined that humans would have great difficulty in weighings at temperatures much below zero. The wind criterion was deferred to a special study (Part 3) since it was hypothesised by APS that wind effects were scale independent but aircraft dependent.

The final selection of the weighing system was to be based on the following criteria:

- Wheel pad thickness.
- Ease of operation, measured subjectively and independently by three APS engineers.
- Pad and system weight.
- Durability and ease of maintenance.
- Accuracy and precision, measured objectively against a non portable bench-mark scale.

- Software capability, measured by analysis and judgement of the APS engineers.

- Weighing surface area.

Cost was intentionally excluded from the selection criteria in view of the requirement for technical defensibility of the results, independent of the cost.

3.2 Experimentation and Comparative Data Acquisitionn

The APS engineers were trained by the manufacturers in the use of the scales. Subsequently, a test case aircraft was weighed with each of the candidate scales and a bench-mark scale for comparison and calibration. Five aircraft were subsequently weighed in a hangar by the APS engineers, using each of the three scales. These aircraft were a Canadair Challenger, a Cessna Conquest, A Piper Cheyenne, Merlin Metroliner and HS-125. Subjective data based on operator experience as well as the objective data relating to measurement were recorded. In addition, the dimensions of the wheel footprint were measured for weight and balance computations and model verification.

While only a limited number of data points were collected during the experimentation, sufficiently consistent qualitative and quantitative data was acquired to make good comparisons.

A mathematical model, known as the Binary Decision Model (BDM), was used to rank the three candidate scales. The composite scores showed the Haenni system to be far superior to the other two systems. Therefore, this system was recommended to TCAG and it was selected for the subsequent studies involving wind effects (Part 3).

3.3 Centre of Gravity Determination

The model which allowed the field determination of the C of G was a simple summation of moments about the nose wheel, with moment arms measured in a dimension along the longitudinal axis of the aircraft. The experimentation showed that an accuracy of ± 2.54 cm could be achieved with this model.

The use of this model required a knowledge of the C of G of the empty aircraft with respect to the nose wheel. Normally, the position of the C of G of the aircraft, as given in the Weight and Balance documents, is a function of an arbitrary datum line. APS recommended that a data base of conversions be maintained for the finite number of aircraft to be inspected in the field.

4. PART 3: WIND EFFECTS AND OVERLOADED SEAPLANE DETECTION

The objectives of Part 3 of the study were twofold:

a) to quantify the effect, if any, of wind on the accuracy and defensibility of the measured weight of the aircraft;

b) to develop an experimental procedure for determining the weight and C of G of seaplanes.

4.1 Wind Effects

This part of the work involved a literature survey and information search, development of a mathematical model, field trails, and wind tunnel tests and analysis to validate the model so that wind effects or weighing limitations could be established.

The literature and information search was found to be quite lacking in very low speed aerodynamics. Therefore, the results of the study were derived from computer modelling and laboratory wind tunnel tests using scaled model aircraft, and experimentation with actual aircraft in field trials.

Two aircraft, a Cessna 206 and a DeHavilland Twin Otter, were weighed in the field under varying wind conditions. Laboratory wind tunnel tests were conducted on an aircraft model similar to a Cessna 210, a SOCATA MS 235.

The conclusions drawn from these tests were that if the wind was from ahead, -90° to +90° to the longitudinal axis, excluding the head-on case, then the measured weight would always be less than the actual weight. Therefore, a reading of "overweight" would truly be overweight.
For winds directly from ahead of the aircraft, it was found that certain instabilities occurred due to form drag. Therefore, it was recommended that aircraft not be pointed directly into wind for measuring.

A limitation of 10 knots in steady wind speed was established above which weighing should not be undertaken. Time and budget constraints prevented further experimentation in winds above this value.

4.2 Seaplane Weight and C of G

The methodology for measuring seaplanes evolved from the development and analysis of a conceptual model based on the "weight by buoyancy" principle, and from field tests of the proposed solution with an actual seaplane.

This proof of concept approach was investigated with one type of float, for which the manufacturer provided a complete set of drawings. The float was the C-3500 of the PEE KAY Float Division of the De Vore Aviation Corporation.

A computer program was developed to calculate the weight of the displaced water as a function of the depth of the float at two discrete locations along the float. The computer program and field test results were compared. The field tests involved taking readings of the "above water line" height of the floats, computing the weight and C of G, then removing the aircraft from the water and weighing it on the most suitable scales identified in Part 2 of this study (Haenni).

It was found that for this test case, weights could be determined to an accuracy level of approximately 2.7 %. Therefore, it was recommended that the computer model be developed for all of the floats and seaplanes in service in Canada and an "easy to use" tabular format be provided for TCAG officers to use in the field.

5. FINAL CONCLUSIONS AND RECOMMENDATIONS

This study has identified the Haenni as the most suitable scale for use by TCAG in its enforcement role. It satisfied all but one element of the revised specification (system weight). Additional tools involving C of G calculations, weight compensation for wind effects, and measuring seaplanes have also been provided which, if applied, would enhance weighing accuracy and reliability. However, the adequacy of the data base from which the conclusions have been drawn remains somewhat limited. This

may affect the defensibility of the application of these tools in a court of law.

In view of the importance of enhancing the limited data base, it is recommended that, in an initial period, TCAG conduct weight checks on only those aircraft considered in this study, and conduct the checks under similar conditions. Through compilation and evaluation of the field data thus obtained from the TCAG officers, it would be possible to enhance the experimental data base. This would permit the definition of any further testing and/or procedures development that may be required to provide a fully validated aircraft weighing system.

Finally, the issue of political and public acceptability of random weight checks of aircraft needs to be addressed. This issue was beyond the mandate of this study. However, the consultants believe that a public information program on the need for "spot checks" would be required, since the paying public will be the most inconvenienced by such checks on aircraft loaded with passengers.

SOMMAIRE

1. INTRODUCTION

En 1988, le Centre de développement des transports (CDT) a confié à Aviation Planning Services Ltd. (APS) le mandat de déterminer s'il existe sur le marché une bascule de pesage portable pouvant satisfaire aux spécifications de performances établies par Transports Canada en matière de détection des aéronefs en surcharge. Ces spécifications avaient été élaborées par la Direction Législation et application des règles du Groupe Aviation, Transports Canada.

Une première étude, achevée en février 1989, avait permis de trouver le matériel recherché et de déterminer les lacunes dans les données d'utilisation. Une deuxième, lancée en 1990, a permis de combler ces lacunes par des expérimentations sur le terrain, tout en s'attaquant aux questions pratiques relatives au pesage d'aéronefs sur le terrain, notamment celle de l'effet dû au vent sur le résultat des pesages. Elle a enfin permis de déterminer les méthodes à suivre pour la détermination du poids brut des hydravions et des avions à flotteurs.

Le présent rapport récapitule les travaux entrepris, donne les résultats obtenus et traite de diverses autres questions : évolution des spécifications, résultat de recherches, conclusions et recommandations sur des moyens efficaces et sûrs permettant aux agents du Groupe Aviation de déceler les aéronefs en surcharge par des pesages ponctuels et dont ils pourront défendre les résultats devant un tribunal.

Les résultats des travaux achevés font l'objet de trois rapports distincts, repris in extenso à la fin du présent sommaire. Ce sont les suivants :

PARTIE 1 - Spécifications et évaluation des matériels, février 1989.

PARTIE 2 - Essai des matériels et calcul du centre de gravité, mai 1990.

PARTIE 3 - Effet du vent et détection des hydravions en surcharge, août 1990.

2. PARTIE 1 : SPECIFICATIONS ET EVALUATION DES MATERIELS

2.1 Spécifications

L'étude achevée en 1988 a permis de réaliser un consensus sur les spécifications à respecter et les critères de sélection à retenir, à savoir :

- encombrement de la bascule
- poids du système
- charge maximale (capacité du système)
- plage des températures de service
- hauteur de la bascule
- maintenabilité et fiabilité du système
- prise en compte de l'effet du vent
- responsabilités et risques associés à la manoeuvre et au levage d'aéronefs coûtant cher

Les spécifications originales stipulaient un encombrement de 61 x 76 cm, un poids maximal de 23 kg, une capacité de 90 720 kg, une plage de températures de service entre - 30 et + 35 °C, une hauteur de 2,54 cm et un moyen pour la prise en compte de l'effet dû au vent.

Les matériels sur le marché à l'époque ne satisfaisant pas aux spécifications du Groupe Aviation, il a fallu relâcher certaines exigences. L'encombrement acceptable a été porté à 61 x 102 cm, le poids maximal à 91 kg, la

capacité maximale ramenée à 29 484 kg et la limite inférieure de la plage des températures de service remontée à 10 °C.

Bien que les spécifications originales stipulaient un moyen pour la prise en compte de l'effet du vent, le Groupe Aviation a fini par trouver acceptable l'idée de la remplacer par une vitesse de vent limite, au-delà de laquelle le pesage ne devra pas se faire.

Le tableau 1 montre les spécifications originales et modifiées, les critères de sélection retenus avec, en regard, les valeurs pondérées correspondantes et, enfin, les résultats comparatifs pour les trois bascules essayées. Il est facile de comparer les chiffres indiqués sous Performances aux valeurs prescrites par le Groupe Aviation. Sous les colonnes Cotation sont donnés les résultats de l'analyse binaire décrite dans les parties 1 et 2 du rapport. A noter que la bascule Haenni été celle qui a donné systématiquement les meilleurs résultats, ayant obtenu une cotation globale de 37,5 et de 41,7 p. 100 à l'égard des essais des parties 1 et 2, respectivement.

2.2 Evaluation des matériels

Des vingt fabricants ayant été sollicités, seuls trois ont pu fournir un matériel répondant aux critères finalement retenus. Il s'agit de Haenni (dont le matériel était déjà utilisé au Québec et en Ontario par Transports Canada), PAT Equipment dont le matériel est utilisé par le ministère des Transports de l'Ontario, et Intercomp, fournisseur du service de police de Gatineau.

Etant donné qu'il n'existait pas de données sur l'utilisation des matériels fabriqués par PAT et Intercomp, et que le matériel Haenni avait donné des

Tableau 1
SOMMAIRE DES SPÉCIFICATIONS ET DES PERFORMANCES CONSTATÉES

CRITÈRES	SPÉCIFICATIONS TRANSPORTS CANADA		COTATION PONDÉRÉE		FABRICANTS								
					HAENNI			PAT EQUIPMENT			INTERCOMP		
	ORIGINALES	MODIFIÉES	PARTIE 1*	PARTIE 2*	PERFORMANCES	COTATION PARTIE 1	COTATION PARTIE 2	PERFORMANCES	COTATION PARTIE 1	COTATION PARTIE 2	PERFORMANCES	COTATION PARTIE 1	COTATION PARTIE 2
ÉTENDUE SURFACIQUE BASCULE (cm x cm)	61 x 76	61 x 102	17,9%	3,6%	36 x 66	6	2	38 x 56	3	1	38 x 57	9	1
HAUTEUR BASCULE (cm)	max. 2,54 cm	approx. 2,54 cm	21,4%	25,0%	2	11	13	3,0	7	8	4,3	4	4
POIDS TOTAL (kg)	23	91	14,3%	17,9%	50 (14,5/bascule)	2	9	76 (22,5/bascule)	6	5	70 (21,7/bascule)	6	5
MAINTENABILITÉ/FIABILITÉ	qualitative	qualitative	25,0%	14,3%	–	10	2	–	10	7	–	4	5
CAPACITÉ (kg) 3 BASCULES	90 720	29 484	10,7%	S/O	30 000	4	S/O	30 000	4	S/O	30 000	2	S/O
PLAGE DES TEMPÉRATURES (°C)	–35 à +35	–10 à +35	7,1%	S/O	–20 à +50	2	S/O	–10 à +40	4	S/O	–28 à +50	1	S/O
CALCUL DE L'EFFET DÛ AU VENT	oui	remplacé par une limite de vitesse de vent	3,6%	S/O	remplacé par une limite de vitesse de vent	1	S/O	remplacé par une limite de vitesse de vent	1	S/O	remplacé par une limite de vitesse de vent	1	S/O
FACILITÉ D'UTILISATION	qualitative	qualitative	S/O	21,4%	–	S/O	11	–	S/O	5	–	S/O	5
PRÉCISION	–	–	S/O	10,7%	–	S/O	4	–	S/O	5	–	S/O	2
FONCTIONNALITÉS LOGICIEL	–	–	S/O	7,1%	–	S/O	2	–	S/O	2	–	S/O	4
COTATION GLOBALE			100	100		37,5	41,7		35,7	33,7		26,8	24,9

S/O = sans objet

Source : Aviation Planning Services Ltd.

* Partie 1, Partie 2 : renvoient aux valeurs prises en compte durant les diverses phases de la recherche et consignées dans les parties 1 et 2, respectivement, du présent rapport. L'évolution des valeurs prises en compte est due à une familiarisation de plus en plus grande de la part des chercheurs aux matériels essayés et aux manipulations successives. Elle est également due à l'élimination des critères auxquels les trois bascules ont pu satisfaire.

résultats mixtes aux yeux des utilisateurs du Québec et de l'Ontario, le contractant a dû recommander une étude spéciale comprenant des essais sur le terrain dans le but de déterminer le matériel le plus approprié.

En plus de mettre en évidence l'insuffisance des données d'utilisation, cette partie du rapport a montré la nécessité de méthodes permettant de localiser le centre de gravité (c.g.) des aéronefs, de calculer l'effet du vent sur les résultats et de peser les hydravions et les avions à flotteurs. Le contractant a donc recommandé que, en plus de parvenir à la sélection de la bascule portable la plus appropriée, il fasse également des recherches sur des techniques pratiques permettant de peser les aéronefs sur le terrain et d'en localiser le c.g.

3. PARTIE 2 : ESSAI DES MATERIELS ET CALCUL DU CENTRE DE GRAVITE

Dans la partie 2, les critères de sélection et les essais sur le terrain ont été affinés et amél orés dans le but d'atteindre l'objectif fixé, et un modèle a été réalisé permettant de localiser le c.g. d'un aéronef par rapport soit à la roue de nez, soit à la roulette de queue.

3.1 Critères de sélection

Les critères indiqués dans le tableau 1 pour la sélection du matériel optimal ont été affinés à mesure que les chercheurs se familiarisaient davantage avec les trois systèmes en présence. La capacité a cessé d'être un critère étant donné que ceux-ci donnaient satisfaction sur ce plan. De même, la limite inférieure de la plage des températures de service a été relevée puisqu'il est difficile à quelqu'un de procéder à des pesages alors que la température ambiante est bien au-dessous du point

de congélation. Enfin, le critère du vent a été renvoyé à une étude spéciale (partie 3) étant donné que, selon l'hypothèse du contractant, l'effet dû au vent est un facteur propre à l'aéronef et pas à la bascule.

Les critères de sélection finalement retenus ont été les suivants :

- hauteur de la bascule;
- facilité d'utilisation, telle que ressentie subjectivement par trois chercheurs agissant séparément;
- poids total;
- durée de vie et facilité d'entretien;
- fidélité et exactitude, par rapport à une bascule témoin non portable;
- fonctionnalités du logiciel, d'après le jugement et l'expérience des chercheurs;
- étendue surfacique de la bascule.

Le facteur coût a été délibérément écarté puisque les performances devaient se justifier sur le plan technique et pas du tout sur le plan économique.

3.2 Expérimentations et saisie de données comparatives

Après avoir été entrainés par les fabricants à l'exploitation des matériels respectifs, les chercheurs d'APS ont procédé au pesage d'un aéronef témoin sur chacun des trois matériels en présence ainsi que sur la bascule témoin aux fins de comparaison et d'étalonnage. Par la suite, les cinq aéronefs suivants ont été pesés dans un hangar par les chercheurs d'APS sur chacune des trois bascules en lice : Challenger (Canadair), Conquest (Cessna), Cheyenne (Piper), Metroliner (Merlin) et HS-125 (Hawker-Siddely), et les données correspondantes, tant subjectives qu'objectives, enregistrées. De plus,

l'empreinte au sol des roues a été mesurée pour permettre de procéder à des calculs de pesage et de centrage ainsi qu'à la validation du modèle.

Malgré le nombre peu élevé des points de mesure, les expérimentations ont permis l'acquisition de données qualitatives et quantitatives suffisamment cohérentes pour autoriser des comparaisons valables.

Les chercheurs se sont servis d'un modèle mathématique binaire (Binary Decision Model) pour hiérarchiser les résultats. Ceux-ci ont montré que la bascule Haenni donne des performances de loin supérieures à celles des deux autres. C'est donc cette bascule qui a été recommandée et qui a été retenue aux fins des études ultérieures sur l'effet dû au vent (partie 3).

3.3 Calcul du centre de gravité des aéronefs

Pour localiser sur le terrain le centre de gravité des aéronefs, les chercheurs se sont servis d'un modèle qui fait la sommation de tous les moments par rapport à la roue avant, les distances prises en compte étant mesurées dans le sens de l'axe longitudinal de l'aéronef. Ce modèle a affiché une précision de calcul de l'ordre de ± 2,54 cm.

Pour utiliser ce modèle, il faut situer au préalable le centre de gravité par rapport à la roue avant de l'aéronef sans chargement. Normalement, le c.g. est indiqué sur le feuillet de chargement et de centrage par rapport à une ligne de référence fixée arbitrairement. APS a recommandé qu'une base de données soit disponible permettant de convertir les distances limites du c.g. en distances par rapport à la roue avant, et ce à l'égard des aéronefs utilisant le terrain d'aviation concerné.

4. Partie 3 : Effet du vent et détection des hydravions en surcharge

Les objectifs fixés à la partie 3 ont été les suivants:

a) chiffrer l'effet du vent sur le résultat du pesage d'un aéronef;
b) mettre au point une méthode expérimentale pour le pesage des hydravions et pour en localiser le c.g.

4.1 Effets dus au vent

Cette partie de la recherche a nécessité une recherche documentaire, la réalisation d'un modèle mathématique, des essais sur le terrain, des essais en soufflerie et des travaux analytiques dans le but de valider ce modèle de manière à pouvoir chiffrer les effets dus au vent et à connaitre les limites de chargement.

La recherche documentaire a abouti à de maigres informations sur l'aérodynamisme aux très faibles vitesses. Les chercheurs se sont donc tournés vers la modélisation, les essais dans une soufflerie de laboratoire sur des maquettes et des essais de vol en vraie grandeur.

Deux avions, un Cessna 206 et un deHavilland Twin Otter ont été pesés sur le terrain dans des conditions de vent variées. Par ailleurs, des essais en soufflerie ont été menés sur la maquette d'un avion ressemblant au Cessna 210, un SOCATA MS 235.

Les résultats de tous ces essais ont montré que, lorsque le vent souffle en direction de l'avion à un angle allant de - 90 à + 90° par rapport à l'axe longitudinal, exclusion faite d'un vent debout, le poids mesuré doit dans tous les cas être inférieur au poids réel. Ainsi, une lecture de surcharge correspondrait effectivement à un état de surcharge. Par vent debout, certaines instabilités peuvent se manifester, dues à la traînée de forme. Il est donc recommandé de ne pas peser un aéronef dans des conditions de vent debout.

Il a été également recommandé de ne pas procéder au pesage d'aéronefs lorsque le vent souffle à une vitesse constante supérieure à 10 noeuds. Des recherches à des vitesses supérieures à cette limite n'ont pu être faites pour des raisons budgétaires et de manque de temps.

4.2 Pesage et centrage des hydravions

La méthode appliquée pour le pesage des hydravions s'appuie sur un modèle d'analyse fondé sur le principe de l'hydrostatique, et sur des expérimentations en vraie grandeur destinées à l'éprouver.

Le bien-fondé de cette méthode a été approfondi par des recherches menées sur un flotteur pour lequel le fabricant avait fourni tous les plans nécessaires. Il s'agit du flotteur C-3500 fabriqué par la division PEE KAY Float de la De Vore Aviation Corporation.

Un programme informatique a été élaboré pour calculer le poids de l'eau déplacée en fonction de la profondeur d'immersion du flotteur, mesurée en deux points précis situés sur son axe longitudinal. Les résultats des essais théoriques ont été comparés aux essais pratiques. Ceux-ci ont été menés comme suit : lectures de la distance au-dessus de la flottaison, calcul du poids et

du c.g. et pesage de l'hydravion au sol sur la bascule sélectionnée (Haenni, voir partie 2).

Ces travaux ont montré qu'il est possible de déterminer le poids de l'aéronef à 2,7 p. 100 près. Il a donc été recommandé que le programme informatique soit étendu à tous les hydravions et avions à flotteurs en service au Canada et qu'une version simplifiée, sous forme tabulaire, soit remise aux agents du Groupe Aviation.

5. Conclusions et recommandations

La recherche a montré que la bascule Haenni convient le mieux aux fonctions de contrôle du Groupe Aviation. Elle a satisfait à tous les critères révisés sauf un, celui de poids. Elle comporte des outils de calcul du c.g. et de l'effet dû au vent, de pesage et de centrage des hydravions qui, s'ils étaient adoptés, amélioreraient la précision et la fiabilité des résultats. Cependant, la base de données ayant servi à la sélection de la bascule restant limitée, son adéquation reste sujette à caution, au point que la justification de ce choix devant un tribunal en cas de litige pourrait se trouver affaiblie.

Afin d'enrichir la base de données, il est recommandé, dans un premier temps, que le Groupe Aviation ne contrôle que les aéronefs ayant fait partie de la recherche et que les contrôles soient menés dans les mêmes conditions. Les données ainsi obtenues serviront à enrichir la base de données existantes, aboutissant à une définition des essais complémentaires susceptibles de mener à une méthode de pesage qui aura reçu une validation pleine et entière.

En dernier lieu, il faudra tôt ou tard s'attaquer à la question des contrôles de poids ponctuels afin d'en approfondir l'aspect politique et l'aspect acceptation

par le public. Le contractant ne l'a pas fait étant donné que cela débordait son mandat. LÀ-dessus, il estime nécessaire de lancer un programme d'information du public voyageur vu que c'est lui qui aura à subir les inconvénients d'un contrôle, alors que l'avion est chargé et prêt à partir.

PORTABLE WEIGH SCALES FOR

DETECTION OF OVERLOADED AIRCRAFT

PART 1

INCLUDES

INITIAL REPORT ON

PORTABLE WEIGH SCALES FOR

DETECTION OF OVERLOADED AIRCRAFT

PREPARED FOR

TRANSPORTATION DEVELOPMENT CENTRE
RESEARCH AND DEVELOPMENT DIRECTORATE
POLICY AND COORDINATION GROUP
TRANSPORT CANADA

BY

AVIATION PLANNING SERVICES LTD

FEBRUARY, 1989

DISCLAIMERS

The contents of this report reflects the analysis and conclusions of Aviation Planning Services Limited and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

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GLOSSARY OF ABBREVIATIONS

APS	Aviation Planning Services Ltd.
FOB	Free on Board
R & D	Research and Development
ROM	Read Only Memory
TC	Transport Canada
TCAG	Transport Canada Aviation Group
TDC	Transportation Development Centre

E. EXECUTIVE SUMMARY

The objective of this study was to evaluate the availability of weighing equipment to meet Transport Canada performance requirements for use in the detection of overloaded aircraft for regulation enforcement purposes and, if not available, to recommend the most suitable technology for further research and development to achieve performance compliance.

The Transportation Development Centre contracted for this work on behalf of Enforcement and Legislation of Transport Canada's Aviation Group (TCAG).

The study was conducted by Aviation Planning Services Ltd. with performance specifications developed by Enforcement and Legislation and data supplied by manufacturers and users of currently available equipment.

The study methodology involved:

(i) Initial review of performance specifications.

(ii) Product search to identify available equipment which satisfied performance specifications.

(iii) Revision of performance specifications by TCAG to relax some requirements where permissible to more realistically reflect the functional needs and to initially permit some current products to qualify.

(iv) Product evaluation through assessment of quantifiable and qualitative factors.

(v) Priority ranking of performance specifications and comparison of the available products with the criteria using mathematical analysis techniques, to identify the optimal current product.

(vi) Identification of current product deficiencies and potential areas for further research and development which would lead to products or procedures to assist TCAG in the fulfillment of its mandate.

The final performance specification included the following criteria, ranked in order of importance as judged by TCAG officials and APS:

(i) Maintainability/Reliability

(ii) Weight

(iii) Pad Size (ie. size platform on which wheel would be placed).

(iv) Pad Thickness (ie. height of platform above ground).

(v) Weight Bearing/Measuring Capacity

(vi) Temperature Range

(vii) Wind Compensation

Early in the study it was determined that portability was imperative as a criteria of selection since the equipment had to be transported by aircraft or personal car.

Using the above ranking, performance data collected on currently available products and an objective mathematical procedure (binary decision analysis), each of the products was "scored" against the above criteria.

Only three products, manufactured by Haenni, PAT Equipment and Intercomp, ultimately satisfied the final performance specifications.

The results of product evaluation and comparison showed the Haenni and PAT system to be equally satisfactory. Intercomp, for which data on service experience was limited, trailed in third place. Some difficulty was experienced in comparing the products qualitatively, based on the experience of user organizations. Two of the products had not been used in an aviation environment, and one of these had only seen use in Canada for a relatively short period.

The study showed that currently available technology does provide some equipment to approximately satisfy the revised performance specifications of TCAG. However, to be certain of an optimal decision, selection of one product over the others can only be made after field testing of the three potentially acceptable products under controlled and comparable conditions.

In addition, wind compensation, float plane weight verification, and centre of gravity read-out, could be included in a potential research and development effort for the future to enhance the capabilities of technology available to TCAG, Enforcement and Legislation.

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1. INTRODUCTION

At the request of the Transportation Development Centre (TDC) of Transport Canada, Aviation Planning Services has conducted a survey and analysis of various issues related to equipment for weighing aircraft in the field with the objective of identifying one or two optimal products for use by Transport Canada.

The study was motivated by the requirements of Enforcement and Legislation of Transport Canada's Aviation Group (TCAG), whose mandate is to ensure an adequate level of safety in the national civil aviation transportation system. An area of concern in the surveillance of aviation activity is the detection of overloaded aircraft.

1.1 Problem Definition

TCAG currently has no accurate and expedient method of weighing aircraft in the field. While two of the regional offices (Cntario and Quebec) from amcng the six enforcement regions have acquired some equipment in the form of "portable weigh scales", the results have been unsatisfactory for two reasons. First, a consistent set of results has not been achieved, and second, all of the requirements as currently defined by TCAG have not been met.

1.2 Methodology

The study methodology in general followed the presentation format of this report and could be described by the sequence of the following elements:

i) Identification and evaluation of current requirements and specifications.

ii) Survey of current distributors and manufacturers.

iii) Analysis of "off-the-shelf" equipment available from the respondents of element (ii) above.

iv) Redefinition of criteria of acceptability of equipment in conjunction with TCAG.

v) Final analysis and evaluation of current equipment with modified criteria from element (iv) above.

vi) Identification of deficiencies and potential areas for research and development.

1.3 Report Statement

This report presents the details of the work and the status of the findings as described in Section 1.2 above and is intended for internal use by Transport Canada. While every effort has been made to acquire and use the latest and most accurate data available, the consultants disclaim any responsibility for misrepresentations, inaccuracies or incomplete data provided by the respondents to the questionnaire or to telephone requests.

2. INITIAL SELECTION CRITERIA AND PERFORMANCE REQUIREMENTS

Through a review of the documentation supplied by TDC and discussions with officials of TDC, seven criteria were initially identified as being relevant for this study. These are described in this section in some detail, including the units of measurement along these criteria. A discussion of the relative importance of these criteria is deferred to a subsequent section dealing with objective methods to establish relative ranks of criteria and the scores of competing products along these criteria.

Among the criteria used to screen potential weighing equipment, portability was the major element as carriage in Transport Canada aircraft and personal/company cars was the planned method of transport to and from the application sites. Only the equipment which could be defined as "portable weigh scale" was to be evaluated. The component criteria which provided a measure of "portability" included weight and size. Five performance related criteria were identified as relevant to this analysis which, along with the two portability criteria, are described in the following subsections.

2.1 Portability Criteria

2.1.1 Wheel Pad Size

In view of the distance between the three sets of wheels of the aircraft to be weighed, the potential weigh scales had to consist of physically independent mechanisms (possibly hardwired together), each of which could be placed under a wheel. Each such mechanism was defined as a wheel pad.

This criteria was relevant only for those systems which did not use a load cell/jack system, where, the size of that system would be relevant. However, load cell/jack systems were not considered suitable for this application (see section 2.2.6).

The size of a wheel pad unit, in terms of volumetric requirements whilein transit was an appropriate measure of one aspect of portability. The only constraint along this criteria was the volume available in TC aircraft or automobiles.

2.1.2 Weight of System

This criteria was relevant due to weight limitations in TC aircraft. The initial TCAG specification limited the total system weight to 50 lbs.

2.2 Performance Criteria

2.2.1 Maintainability/Reliability

In addition to the obvious requirements to have dependable, trouble free equipment, this criteria emphasised the dependence which would be placed on the results generated by the equipment for the purposes of law enforcement. Measurements along this criteria would be based on historical data to be gathered from current users if any could be found.

2.2.2 Wheel Pad Thickness

This criteria applied also only to the non jack type weigh scales. Measurement along this criteria was simply the height of the platform above the ground. The criteria was important for the following reasons:

i) The horizontal force required to position an aircraft over the pad is a function of the height and slope of the ramp to that height. As the height increases, either a longer ramp or a steeper ramp is required. This in turn increases the weight of the system and/or the required horizontal forces to move the aircraft.

ii) On most propeller driven aircraft, especially low wing monoplanes, the wheels are longitudinally aligned with the thrust line of the engines. The propeller axis also lies along this thrust line. If an aircraft is powered onto the pad under its own power, potential for propeller damage exists before and during the initial climb up the ramp, if the pad thickness is excessive.

2.2.3 System Capacity

System capacity was defined as the maximum weight of aircraft which could be weighed. The initial TCAG specification was to weigh aircraft up to 200,000 lbs., which would have included aircraft up to the size of B-727.

2.2.4 Operating Temperature Range

This criteria identified the range over which the weigh scale would be called to service with an expectation of reliable results. This was initially specified by TCAG as $-30^{o}C$ to $+35^{o}C$.

2.2.5 Wind Compensation

Since aircraft wings and other surfaces are aerodynamically designed, any airflow over them causes forces. Therefore, wind can undermine an aircraft load measuring system's

capability to provide accurate results. If the airfoil is pointed into wind, the reading of weight will generally be less than actual. Conversely, if the wind is blowing from behind the aircraft, the reading will be exaggerated. For any other direction of wind, varying vectors and degrees of moments would be generated. The initial specification by TCAG required weight read-out capability from the weigh scales with the aircraft positioned in up to 10 knot wind speeds.

In the judgement of the consultants, wind effects could be quantified only as functions of specific aerodynamic characteristics of the aircraft undergoing the weighing and the wind vector. Therefore, initially, this criteria was included in the list of criteria but not used to select or reject any potential weigh scales.

2.2.6 Liability and Risk

Although not specifically identified as a criteria in the specifications of TCAG, the issue of liability and risk in terms of potential damage to the aircraft was considered quite important. For example, jacking up a random aircraft type in the field under various surface and environmental conditions is inherently more dangerous than simply rolling it onto a ramp led platform.

3. PRODUCT ANALYSIS - CRITERIA REVIEW CYCLE

It became evident during the early stages of this study that an iterative approach would be required in the selection process since the initial set of criteria could not be satisfied by any current product. This section describes this iterative process and elaborates on its various phases.

3.1 Current Product Inventory

A list of potential suppliers and manufacturers of portable weigh scales was generated from the World Aviation Directory and supplied TDC documentation. An exhaustive list of twenty-one organizations world wide was established. This list is shown as Table 3.1.

Data on available products which could approximately meet the criteria presented in Section 2 was requested from each organization listed in Table 3.1. From the twenty-one organizations, four were non-respondents, eight had no suitable products to meet the appropriate criteria, and three were simply distributors for manufacturers. The end result was a source list of six manufacturers who produced potentially satisfactory equipment. These six manufacturers, their products, and parameter values along a selection of the criteria identified in Section 2 are shown in Table 3.2. The last row entry of Table 3.2 summarizes, for comparative purposes, the initial TCAG specifications along the listed criteria.

TABLE 3.1
SUPPLIERS/MANUFACTURERS
OF
PORTABLE WEIGH SCALES

COMPANY	TELEPHONE	STATUS	RETAINED
1. International Road Dynamics	306-955-3626	Received Material (same as Evergreen)	
2. PAT Equipment Corp.	717-765-4466	Received Material	Retained
3. BrantFord Scales Ltd. (Haenni)	519-752-3701	Received Material	Retained
4. Evergreen Weigh	203-269-7701	Received Material	Retained
5. Revere Corp.	697-9245	Received Material	Retained
6. Howe Richardson Inc. (General Electrodynamics)	817-572-0366	Received Material	Retained
7. Intercomp	612-476-2531		
8. Glesco Eqpt. (Malabar)	337-2260	Received Material	
9. CMI Dymanics	514-683-1301	No Product Available	
10. Canada Scale Co.	603-926-1200	Received Material (same as Evergreen)	
11. Centro Manufacturing	416-259-1111	No Product Available	
12. Pacific Aerodyne	416-673-0054	No Product Available	
13. Jet Support Corp.	213-665-7462	No Response	
14. GMDC Inc.	206-824-9048	No Response	
15. A.O.G. Aviation Supply Inc.	213-208-2175	No Product Available	
16. USATCO/AIR WORLD	602-951-8530	No Response	
17. Avia-Sonic Corp.	516-352-2217	No Response	
18. Toledo Scale	301-990-0954	No Product Available	
19. Bridge Weighing Systems, Ohio	514-381-7267	No Product Available	
20. Penwalt Co. (Piezo film only) PA	216-229-8400	No Product Available	
21. Streeter-Richardson, Graylake, Il	215-666-3547	No Product Available	
	312-233-4801		

Source: World Aviation Directory

TABLE 3.2

MANUFACTURERS AND CHARACTERISTICS
OF
PORTABLE WEIGHING EQUIPMENT

		TYPE OF SCALE	SELECTED CRITERIA FOR EVALUATION AND PARAMETRIC VALUES									
MANUFACTURER	MODEL #	LOAD CELLS (JACKS)	WHEEL PAD DESCRIP/CAPACITY	WHEEL PAD SIZE (inches)	TOTAL WEIGHT OF SYSTEM	CAPACITY	ACCURACY	READ-OUT	READ-OUT LBS or KILOS	OPERATING RANGE TEMPERATURE (C)	PRINT-OUT CAPABILITY	POWER SUPPLY	LIST PRICE ($US)
EVERGREEN WEIGH Inc. Lynnwood, WA.	Roadrunner I	N/A	1000 to 15000 lbs per pad (set of 3) 9 deg. slope ramp	13L x 14W x 2 3/4H (for 1000 and 2000 lbs pads) 17L x 17W x 4H (for 5000 lbs + capacity)	19 lbs per pad (2k lbs or less) 50 lbs per pad (5k lbs or more) (9 lbs indicator)	1000 to 15000 lbs per pad	+- 0.1% (tires centered) +-0.2% (tires off-center) EMI protected	Liquid Crystal Display (LCD)	Both	-18c to +50c (LCD limits)	Available	115V AC 220V AC 12V DC (12 hrs rechargeable battery)	$ 2650 to $ 6900
		N/A	50000 lbs per pad (set of 3) 3 deg. slope ramp			50000 lbs per pad	+- 0.1% (tires centered) +-0.2% (tires off-center) EMI protected	Liquid Crystal Display (LCD)	Both	-18c to +50c (LCD limits)	Available	115V AC 220V AC 12V DC (12 hrs rechargeable battery)	$ 17000
		set of 3 (optional)	N/A	N/A		5000 lbs per Load Cell Other capacities available	+- 0.1% (EMI protected)	Liquid Crystal Display (LCD)	Both	-18c to +50c (LCD limits)	Available	115V AC 220V AC 12V DC (12 hrs rechargeable battery)	$ 5000
	Roadrunner II	set of 3	N/A	N/A	67 lbs (6 to 9 lbs for each load cell) (9 lbs for indicator)	15000 lbs 50000 lbs or 100000 lbs per Load Cell	+- 0.1% (EMI protected)	Liquid Crystal Display (LCD)	Both	-18c to +50c (LCD limits)	Available	115V AC 220V AC 12V DC (18 hrs rechargeable battery)	$ 6500 $ 6800 $ 7500
REVERE CORP. Wallington, CT.	Jetweigh	set of 3	N/A	N/A	72 lbs for all models except for the 100000 lbs Load Cell cap. (96 lbs)	5000 lbs 10000 lbs 25000 lbs 50000 lbs or 100000 lbs per Load Cell	+- 0.1% of applied load or +- 0.2% of channel cap. whichever is greater (EMI protected)	Liquid Crystal Display (LCD)	Both	0c to +50c	Available	28V DC 115V AC 220V AC	$ 9733 $ 10072 $ 11103 $ 11103 $ 16507
HAENNI Switzerland dist. by BRANTFORD SCALE Ltd Brantford, ONT.	DC 100 Ind. WA. 102 Wheel Pads	N/A	Set of 3 only 1/2" thick	38L x 15W x 1/2H	3 pads @ 50 lbs Ind. & 16 lbs Total aprox 200 lbs (including carrying case + accessories)	22000 lbs per pad	+- 70 kgs or +- 154 lbs	Liquid Crystal Display (LCD)	Only Kilos	-3c to 30c	Standard	12V DC 110V AC 220V AC	$ 35500 est.

SOURCE : Manufacturers' and Suppliers' Data.

TABLE 3.2, CONTINUED

MANUFACTURERS AND CHARACTERISTICS
OF
PORTABLE WEIGHING EQUIPMENT

		TYPE OF SCALE		SELECTED CRITERIA FOR EVALUATION AND PARAMETRIC VALUES								
MANUFACTURER	MODEL #	LOAD CELLS (JACKS)	WHEEL PAD DESCRIP/CAPACITY	WHEEL PAD SIZE (inches)	TOTAL WEIGHT OF SYSTEM	CAPACITY	ACCURACY	READ-OUT	READ-OUT LBS or KILOS	OPERATING RANGE TEMPERATURE (C)	PRINT-OUT CAPABILITY	POWER SUPPLY	LIST PRICE ($US)
GENERAL ELECTRO Corp (G C E) dist. by NOUE RICHARDSON Inc Montreal	GEC P4	N/A	[3 pads for 72k lbs capacity or less [5 pads for 72-120k lbs capacity	39W x 30L x 41/2H	Aprox. 140 lbs per pad [Total aprox. 500 lb (3 pads + 1 ind. + carying case)	Aircraft gross weight of 0-120000 lbs (24000 lbs per pad)	+- 0.1% or +- 5 lbs whichever is greater	[Liquid Crystal Display (LCD)	Both	0 to +50c	Available	Wheel pad: 40 VDC Ind.: 115 VAC	$34000 (3 pad kit) with entry ramps
	GEC MP500E	N/A	[3 pads for 60k lbs capacity or less [5 pads for 60-100k lbs capacity	14W x 20 1/2L x 3 1/8H	50 lbs per pad	Aircraft gross weight of 0-100000 lbs (20000 lbs per pad)	+- 1.0% [+- 0.5% with temp. var. curve)	[Liquid Crystal Display (LCD)	Both	-18c to +50c	N/A	Indicator N/A	$2795 US per pad
PAT EQUIPMENT Corp dist. by Aidio consultants Montreal	[SAUTO-C Wheel Pads + SAW 300 [Indicator/ Printer	N/A	Set of 3 or 5 only 1.1" thick	31.7W x 20L x 1.1H	3 pads @ 40 lbs ind. @ 26 lbs [Total aprox 200 lbs] [(including carrying [case + accessories)]	Aircraft gross weight of 0-110000 lbs (22000 lbs per pad)	[+- 25 kgs from 0-2500 kgs (55 lbs) (0-5512 lbs)] [+- 50 kgs up to 10000 kgs (110 lbs) (22046 lbs)]	[Liquid Crystal Display (LCD)	Both	-10c to 50c	standard	[Wheel pads: 6 recharg batteries (size AA) Ind./Printer: 10-15 V recharg. battery (DC)	$24600cdn (4300/pad 8000/ind.)
INTERCOMP. dist by [Balances Canadiennes Montreal	LP 600 Pads [PT 20 Computer/Printer	N/A	Set of 3 or 5 1.5" thick	30W x 16L x 1.5H	3 pads @ 40 lbs ind. @ 10 lbs [Total aprox 175 lbs] [(including carrying [case + accessories)]	Aircraft gross weight of 0-100000 lbs (20000 lbs per pad)	+- 1.0% static (+- 2.0% rollower)	[Liquid Crystal Display (LCD)	Both	-20c to 50c (for pads) +5c to +35c [(for comp./ printer)	standard	12V DC 110V AC 220V AC Recharg. batteries for both pads/printer	$3295/pad $2022/print
Transport Canada Requirements for Comparative Purposes		N/A	Wheel Pads only Max thickness 1"	Max Dimensions: 30L x 24W x 1H	Max Weight of whole unit: 50 lbs	Aprox. 20000 lbs per pad/load cell [for aircraft gross weight up to 200000 lbs	Not mentioned. Must have built-in [calibration/test device. Built-in determination of c.g. desirable. [Wind compensation desired]	Indicator to [provide single] [pad readout as [well as total weight	Both	-35c to 35c	[Desirable	[Portability dictates the use of a rechargeable battery in conjunction with an adaptable battery charger (110/220V AC)	

SOURCE : Manufacturers' and Suppliers' Data.

3.2 Review of TCAG Specifications

From a comparison of the TCAG specifications and the available products in Table 3.2, it was determined that currently available products did not satisfy all of the TCAG specifications. Therefore, given these preliminary results, a joint decision by the client and the consultants resulted in a request for review of the TCAG specifications. This review was conducted by Enforcement and Legislation following guidelines prepared by the consultants. These guidelines included comments and questions with respect to the evaluation criteria, currently available products, and products on the near horizon. A typed copy of the questionnaire and response from Enforcement and Legislation is attached as Appendix A. The re-formulated specifications are shown in Table 3.3.

Weight, size, and temperature constraints were relaxed somewhat during this specifications review process.

3.3 Other Considerations

This subsection presents some additional considerations highlighted by the study.

3.3.1 Wheel Pad Thickness

As a consequence of wheel pad thickness, the procedure for positioning the aircraft onto the scales under its own power was criticized by the users of one of the current systems (Haenni). It appears that, despite the goodwill of the pilot involved, accurate positioning of the aircraft was very difficult to achieve. In some cases, pilots were very reluctant to allow their aircraft to be weighed and resorted to

TABLE 3.3
HISTORY OF
TCAG SPECIFICATIONS
DEVELOPMENT

PERFORMANCE SPECIFICATIONS		CAPACITY AIRCRAFT GROSS WEIGHT	PAD SIZE	PAD THICKNESS	SYSTEM WEIGHT	TEMPERATURE RANGE	WIND COMPENSATION
INITIAL	IMPERIAL	200,000 lbs	24" x 30"	Max 1"	50 lbs	-35°C to +35°C	DESIRED
	METRIC	90,720 kg	61cm x 76cm	Max 2.54cm	23 kg		
REVISED	IMPERIAL	65,000 lbs	24" x 40"	Approx 1"	200 lbs	-10°C to +35°C	WIND LIMITATIONS ACCEPTABLE
	METRIC	29,484 kg	61cm x 102cm	Approx 2.54cm	91 kg		

Source: TCAG Documentation

delaying tactics. One user solved the problem by physically pushing the aircraft by hand in order to make it roll properly onto the scales. This was reported as a viable procedure for aircraft of all size/weights up to the Twin Otter category and was described as a much safer procedure. For larger-/heavier aircraft, a tow tractor would have to be used. The thickness of the pads was a limiting factor and only wheel pads with a thickness of approximately one inch (2.54cm.) were recommended.

3.3.2 Wheel Pad Size

A handling problem with the carriage of the Haenni system in a Beech Baron was identified. A possible alternative was the carriage of each component independently in its own case or by the use of a carrying strap or handle. This would alleviate the handling problems associated with the larger single carrying case while still permitting the system to be secured properly in the Baron.

3.3.3 Weight and Pad Thickness

The original specification of 50 lbs. as a maximum system weight could only be achieved by using a load cell/jack system, which was deemed unsuitable. With pads, at roughly 50 lbs. per pad, a three pad system with indicator, cables and accessories would produce a total system weight of approximately 175 lbs. Transport Canada agreed to a maximum aggregate weight of 200 lbs. for the combined system.

Wheel pad systems with a thickness of two inches or more require the mandatory use of entry ramps (typical 24" ramps @ a unit weight of 40 lbs.), which increase the total system weight beyond the maximum allowable limit of 200 lbs. Therefore, thickness and weight were correlated.

3.3.4 Capacity

An aircraft gross weight of 200,000 lbs. was originally specified. It was agreed, however, that for the most part, a capacity of 65,000 lbs. would be sufficient. The Quebec region desires to have the capability of weighing aircraft in the DC-9 category. Since all the indicators/printers surveyed had an eight channel capability, one alternative would be to add two extra wheel pads to the standard three pad system; one pad would be for the nose landing gear and two for each main landing gear (one per wheel). Total system capacity would be increased to 110,000 lbs.(in the case of a 22,000 lbs. unit pad capacity), making it possible to weigh a DC-9 having a maximum take-off weight of approximately 108,000 lbs.. This alternative, however would bring the total system volume and weight outside of the applicable criteria limitations.

3.3.5 Temperature Range

With respect to operating temperature range, the -30°C lower limit of the temperature operating range was quoted as a "worst case scenario". After consultation with Transport Canada, it was agreed that it was very unlikely that Inspectors will be weighing aircraft in temperatures of less than -10°C. The upper end of the range was set at +35°C.

The salient observations from the review was that load cells were not acceptable. Therefore, the potentially suitable products were reduced to three, namely, products manufactured by Haenni, PAT Equipment and Intercomp. These three products were evaluated with reference to the revised criteria. The process of evaluation is the subject of the next section of this report.

4. PRODUCT EVALUATION

The remaining analysis and evaluation involved an assessment of the three potentially suitable products along the criteria identified in Section 2 and revised by the process described in Section 3.

4.1 User Feedback

While the quantifiable criteria were given numeric values for each product, the criteria of maintainability/reliability, which is also intimately related to user satisfaction, could be determined only through primary data collection. Therefore, a list of current users, who could be conveniently contacted within the time and budget constraints of the study, was secured from the manufacturers. This list is reproduced as Table 4.1.

It should be noted that while the list of respondents is small for statistical significance, in depth interviews with the users have provided extremely useful data on qualitative factors. These are discussed in the following sections for each manufacturer's products.

It was determined that two of the three manufacturers could not identify an aviation environment user of their equipment. Data was available, however, from users in enforcement of highway weight regulations. In the case of the Haenni system, two aviation users, who were inspectors in the Quebec and Ontario regions of TCAG were contacted. They have approximately three years of experience with the Haenni portable weigh scales.

TABLE 4.1
PORTABLE WEIGH SCALE
USER LIST

MANUFACTURER MODEL	ORGANIZATION
HALNNI EC 100 WL 102	Air Carrier Operations Ontario Region Transport Canada
	Quebec Region Transport Canada
PAT Equipment SAW 10 SAW 300	Highway Enforcement Ministry of Transport Ontario
Intercomp LP 600 PT 20	City of Gatineau Police Department

Source: Aviation Planning Services Survey

Each user was contacted by telephone and asked the same series of questions. An overall evaluation of each model was requested as well as any general comments.

The qualitative data obtained from the phone survey is summarized below for each of the three products on the short list.

4.2 Haenni System

The model used in the Quebec region is slightly different from the one used in the Ontario region. In Ontario, a central computer/printer linked to each of the three wheel pads is used to produce a hard copy of the total weight of the aircraft. In Quebec, the output of each scale has to be read independently and manually added up to produce the total aircraft weight.

Operationally, in Quebec, the aircraft taxis onto the scales under its own power. In Ontario, the aircraft is rolled manually onto the scales by a number of persons (normally three or four). The Quebec region has abandoned the use of their portable weigh scales because of a lack of "practicality". However, their reliability was judged excellent, with no reported breakdown. They only required proper handling technique and adequate storage facilities.

The Ontario region contact was, by contrast, very happy with the Haenni system. The weigh scales were reportedly used very frequently in different parts of the province with no reported failures to-date. The reliability and accuracy were reported as excellent even in adverse weather conditions. Required maintenance was minimal and, as stated by the Quebec region, needed only proper handling techniques and storage

facilities. The scales were reported to have been used in a winter environment and in light wind conditions with no problems. The mere availability of such a portable system was reported to contribute to flight safety by keeping the small operators honest in terms of their loading procedures. The only drawback was the strict requirement to use the Haenni system on level, hardened surfaces (concrete or asphalt), restricting its use on surfaces such as gravel or crushed stone. On soft surfaces, where the aircraft load vector may not be perpendicular to the weighing surface, erroneous reading could occur.

4.3 PAT Equipment

This model was reported as very reliable and extremely satisfactory by the user contacted at the Ontario Ministry of Transport. The PAT wheel pads are used on highways throughout the province for enforcement of highway weight regulations and can be used on sand, snow or gravel with the help of optional end plates which increases the overall length of the wheel pads by less than six inches. The scales have been used for a number of years in rain and snow and at temperatures as low as -15°C without difficulty. Some minor problems with the digital read-out were resolved by the manufacturer which reportedly offers an excellent after sale service.

The calibration is regularly checked by the manufacturer during servicing. It was also reported that the majority (75%) of the scales (stationary and portable) used by the Ontario Ministry of Transport were PAT products.

4.4 Intercomp

This portable weigh scale system has been in use for only six months in Canada by the police department of the city of Gatineau, Quebec. The user reported no breakdown, good serviceability and gave it a very satisfactory overall rating. The Gatineau police are presently using two Intercomp systems and have ordered an additional two. The scales have been used in rain and snow with no problems, and the accuracy was reported as excellent at all times.

Given the users' qualitative feedback on the systems and the quantitative parameter values obtained from manufacturers and presented in Section 3, the next phase of the study addressed the selection of one or more systems to maximally satisfy the TCAC specifications. The next section elaborates on the selection process.

5. CRITERIA RANKING AND PRODUCT SCORES

This section describes an objective technique used for ranking the criteria identified in Section 2 and 3, and scoring the three products along each criteria. The ultimate objective was to obtain a relative score for each of the three products such that a relative preference would be indicated, given the set of relevant criteria.

5.1 Binary Decision Analysis Technique

This technique was developed by Westinghouse and adapted by A.P.S. to facilitate the selection process where a number of competing products have to be ranked on the basis of several criteria. It is essentially a systematic, formalized procedure for subdividing a complex array of decisions into decisions involving only one of two choices at a time and then aggregating the results. The details of the technique are presented in Appendix B, while only skeletal basis and results are presented here.

The net result of the application of binary decision analysis is a criteria weighting which reflects the relative importance of the criteria and a composite score for each of the products in the selection process.

5.2 Criteria Weighting

The seven criteria identified in Sections 2 and 3 were compared in pairs to determine relative importance jointly by Transport Canada and A.P.S. The results of the comparisons are summarized in Table 5.1. The columns of the "RAW SCORE" block in the table show the important criteria with a value of 1 when compared to one other criteria at a time. For

example, in a comparison of "maintainability/reliability" with "weight", the former was considered more important than the latter and given a score of 1 while the latter was scored as 0.

From the results of Table 5.1, it is evident that "maintainability/reliability" ranked the highest (weight of 25%) followed by pad thickness (weight of 21.4%), pad size, pad weight and capacity (17.9%, 14.3%, and 10.7% respectively). Temperature range and wind compensation were of less importance with a weight of 7.1% and 3.5% respectively.

5.3 Product Scores

The three products were compared in pairs along each criteria to determine the relative scores. Sections 5.3.1 and 5.3.2 present the rationale for scoring each product on qualitative criteria while 5.3.3 presents a summary of the quantifiable scores.

5.3.1 Maintainability/Reliability

The Haenni and the PAT products were considered equal in terms of maintainability and reliability as determined during the user interviews. The Intercomp model was disadvantaged only due to its relatively short exposure to service since its introduction and comparatively infrequent usage by the Gatineau Police Force in comparison to the other two products which have seen much higher frequency of usage over a longer period.

TABLE 5.1
RESULTS OF CRITERIA WEIGHTING EXERCISE

CRITERIA	RAW SCORE	TOTAL SCORE	TRANS-FORMED SCORE	CRITERIA WEIGHT
Maintainability/Reliability	1 1 1 1 1 1	6.0	7.0	25.0
Weight	0 0 0 1 1 1	3.0	4.0	14.3
Pad Size	0 1 0 1 1 1	4.0	5.0	17.9
Pad thickness	0 1 1 1 1	5.0	6.0	21.4
Capacity	0 0 0 0 1 1	2.0	3.0	10.7
Temperature range	0 0 0 0 0 1	1.0	2.0	7.1
Wind compensation	0 0 0 0 0 0	0.0	1.0	3.6
TOTAL		21.0	28.0	100.0

Source : Aviation Planning Services Ltd.

Notes:

1) Transformed score = Total Raw Score + 1
2) Criteria weight = $\frac{\text{Transformed Score}}{\text{Total of Transformed Scores}}$

5.3.2 Wind Compensation

As suggested earlier in this report, wind influence is judged to be more a function of aircraft aerodynamics and wind vectors than the weigh scales. Furthermore, this criteria was ranked as the least important in the criteria weighting exercise. Therefore, all three products were scored equally along this criteria.

5.3.3 Quantifiable Criteria

The parameter values for each product along each quantifiable criteria were listed in Table 3.2 in section 3. Therefore, when comparing two products at a time, the product with the superior parameter value was scored as 1 while the inferior valued product was scored as 0.

5.4 Individual Product Scores

The complete set of scores for each product along all of the criteria is shown in Table 5.2. The upper part of the table shows the comparison of the products in pairs along each criteria while the lower portion shows the final scores as a percentage of total for each product along the individual criteria.

5.5 Composite Product Scores

The last step in the binary analysis was to combine the weights of the criteria with the individual product scores. This resulted in a single valued parameter which describe the relativc rank of the products. The results of this exercise are presented in Table 5.3 which shows the composite product scores and their final ranking.

TABLE 5.2
DEVELOPMENT OF INDIVIDUAL PRODUCT SCORES[1]

PRODUCT / CRITERIA	MAINT/ RELIAB			WEIGHT			WHEEL PAD SIZE			WHEEL PAD THICKNESS			CAPACITY			TEMP RANGE			WIND		
HAENNI	½	1		0	0		1	0		1	1		½	1		0	1		½	½	
PAT	½		1	1		½	0		0	0		1	½		1	1		1	½		½
INTERCOMP		0	0		1	½		1	1		0	0		0	0		0	0		½	½
	FINAL SCORES[2]																				
HAENNI	41.7			16.7			33.3			50.0			41.7			33.3			33.3		
PAT	41.7			41.7			16.7			33.3			41.7			50.0			33.3		
INTERCOMP	16.7			41.7			50.0			16.7			16.7			16.7			33.3		
TOTAL	100			100			100			100			100			100			100		

NOTES:
1. Individual product scores are either 1 or 0 unless they are equal, in which case, score is ½.
2. Final score for each product, for each criteria is equal to the sum of scores for each product +1 within each criteria, divided by the sum of the scores. For example: for maintainability/reliability, scores for Haenni, Pat, and Intercomp are (1½ + 1), (1½ + 1), and (0 + 1) while the total is 6. Therefore, final score for Haenni under this criteria is (1½ + 1)/6 = 41.7.

Source: APS Analysis

TABLE 5.3
COMPOSITE PRODUCT SCORES AND RANKING

SCALE MODELS	SCORE PER CRITERIA							TOTAL SCORE
	1	2	3	4	5	6	7	
1. HAENNI	10	2	6	11	4	2	1	37.5
2. PAT	10	6	3	7	4	4	1	35.7
3. INTERCOMP	4	6	9	4	2	1	1	26.8
TOTAL								100.0

Source: APS Analysis

CRITERIA INDEX:

1. Maintainability/Reliability
2. Weight
3. Pad Size
4. Pad Thickness
5. Capacity
6. Temperature
7. Wind

NOTES:

1) Composite product score per criteria = Criteria Weight X individual product score per criteria

EXAMPLE: for Haenni, maintainability/reliability composite product score = 25% x 41.7% = 10%(rounded off)

From the results of the binary analysis, it is evident that, of the currently available products, Haenni and PAT respond equally to maximally satisfying the specifications of TCAG. However, to distinguish between the two, other criteria need to be considered.

5.6 Cost Considerations

During the discussions with TCAG officials, it was suggested that cost of the equipment was not a significant factor in the selection process. However, in view of the close results between the PAT and the Haenni products, cost was introduced into the decision process.

The quoted costs were as follows:

- Haenni: $35,500 CAN
- PAT: $24,600 CAN
- Intercomp: $21,000 CAN

All of the above were FOB (North America) exclusive of sales taxes.

Under this inclusion, the PAT product became the leading product.

5.7 Caveat

The major concern in the use of this analysis for decision making has been the lack of sufficient data from field use with the PAT and Intercomp systems in an aviation environment. The Intercomp product is the lowest cost product but is new to Canada and unknown to the aviation user. Therefore,

its score on qualitative criteria was low. However, in time, as more data is available, it may prove to be competitive with the other products.

6. CONCLUSIONS

The results of the analysis suggest that current product inventory is adequate to do some of the work required by TCAG but that a truly satisfactory or optimal product satisfying the original specifications is not available. While the Haenni and PAT products have been shown to be equally good, they both have the advantage of current usage over the Intercomp system. Therefore, an objective and thorough comparison of the three products cannot be claimed in this report.

It is recommended that, pending further developments on the part of the manufacturers, field trials under controlled conditions be conducted with the three systems to secure comparable data on handling characteristics, operational complexity etc. and to determine if one produces significantly better results than the others. These trials would also include the development of special handling procedures, which may minimize problems encountered by current users.

Notwithstanding the above recommendation with respect to the current products, there are areas in which further research and development could be undertaken to enhance the overweight detection capabilities of TCAG. These consider wind compensation, centre of gravity calculation, and the float plane case. The following section addresses these potential improvements separately as an addition to the main conclusions of this study, which dealt with evaluation of commercially available equipment.

7. POTENTIAL RESEARCH AND DEVELOPMENT

Three areas have been identified for further research and development activity with respect to portable weigh scales. These involve wind compensation, built-in calculation of the center of gravity and some means of evaluating the gross weight of float planes in the water.

7.1 Areas of Research

7.1.1 Wind Compensation

The complexity of the problem was recognized unanimously by all the manufacturers. Some of the factors involved include varying airfoil sections on different aircraft types, varying angles of attacks, varying uploads and downloads in a cross-wind, etc. Only one manufacturer, PAT Equipment, has started to address it, and its German subsidiary is presently conducting R & D in this area. The PAT Equipment representative contacted declined to volunteer information on the research project except to say that a preliminary report should be available by the summer of 1989.

In view of the consultant's judgement that wind effects are aircraft and wind vector dependent, it is proposed that the field trials recommended in Section 6 include measurements of wind effects under various aircraft, wind vector combinations to determine the existence and extent of such effects.

7.1.2 Center of Gravity Calculations

None of the three competing systems possess the capability to determine a centre of gravity. However, all of the indicator-/printers have a microprocessor chip with some ROM and RAM

capacity. One of the load cell system indicator/printer, the Revere Group model, has a ROM library of up to 200 aircraft types and the stored information enables the microprocessor to perform an automatic determination of the center of gravity during the weighing process. Therefore, potential to introduce this feature into current products exists.

7.1.3 The Float Plane Case

Most bush pilots have learned through experience to estimate the acceptability of the weight of their aircraft just by observing the longitudinal angle between the water and the floats and the draft of the floats in the water. This visual procedure could be expanded and improved upon by the use of buoyancy markings similar to the ones painted on the hull of ships.

Such a concept could be certified for each aircraft/float combination and would greatly improve the enforceability of the weight and balance regulations. An inspector would periodically check markings and simply have to verify that the water level was at or below the buoyancy markings. Maximum gross weight and center of gravity limitations could be verified with proper conversion tables, which could be developed through experimentation and engineering analysis.

7.2 Research and Development Cost Estimates

This section presents some preliminary estimates of the time and costs required for the conduct of the field trials referenced in Section 6 and the area of research suggested here.

7.2.1 Field Trials of Current Equipment

Ideally, these would involve two or three aircraft of known weight. These aircraft would be manoeuvered repeatedly over the competing products, measurements taken, and accuracies, operational and other complexities recorded for subsequent comparison. Given the availability of aircraft from Transport Canada at Dorval this task could be completed in 10 person-days distributed over two critical seasons to ensure a diversity of environmental conditions for the trials.

7.2.2 Wind Compensation Factors

This research would involve the weighing of several of the commercial aircraft of known weight with scales of known accuracy in varying wind conditions. The results' analysis would lead to a determination of errors due to wind and the possible development of tables with correction factors for specific aircraft types, under specific configurations, weight ranges and wind conditions. This activity could take up to 2 person-days per aircraft type distributed over a month or so to ensure sufficient wind conditions were tested. For twenty aircraft types, for example, it would be possible to achieve economies and possibly complete the trials in 30 person-days.

7.2.3 Centre of Gravity Calculations

The mechanics of forces and centre of gravity calculations is relatively straight forward. A purely theoretical table could be developed to show centre of gravity position relative to one of the wheels. This task would take a qualified person approximately 2 days.

7.2.4 Float Plane Case

A theoretical analysis could be done to determine where markings should be placed to indicate weight of the aircraft. However, as buoyancy is determined by the purity of the water as well as volume of water displaced, some experimentation in salt-water and pure water would be necessary. It is estimated that 10 person-days of theoretical research and analysis and another 10 person-days on some experimentation could be spent.

7.3 Overall Costs

In order to provide a wide base of effective measurement capability, approximately 20 aircraft types which are operated by small air carriers should be included in the R & D described here. The time to conduct the required work would be approximately 60 person-days, distributed over a range of professionals and approximately six months. At an average cost of $600 per day, this would amount to $36,000 exclusive of expenses. Given the availability of aircraft and equipment locally, the expenses should not exceed $2,000.00.

December 16, 1988

APPENDIX A

AVIATION PLANNING SERVICES LTD.

QUESTIONS REGARDING THE TRANSPORT CANADA SPECIFICATIONS ON PORTABLE WEIGH SCALES FOR THE DETECTION OF OVERLOADED AIRCRAFT

For each subject, the rationale behind the formulation of the question is briefly described, followed by the actual question. General comments are invited and will be appreciated.

1. Capacity:

An aircraft gross weight of 200,000 lbs was originally specified. This would permit the weighing of aircraft as large as Boeing B-727's. Is there really such a need? It would seem that an overall capacity of approximately 65,000 lbs would be sufficient and would permit the weighing of aircraft such as HS-748's or F-27's which are really the biggest aircraft that the small operators are using in the northern area. Furthermore, airlines and operators that have DC-9, B-737 or B-727 in their fleet probably require less monitoring and policing when it comes to making sure that such aircraft do not take off overloaded.

Q: Would a weighing capacity of 65,000 lbs be sufficient?

YES

Comments:

For most part, a capacity of 65,000 pounds would be sufficient and would satisfy present needs with the possible exception of Quebec region who have expressed a need to weigh aircraft in the DC-9 category. If scales of higher capacity are available or could be developed, future requirements would be taken into consideration as it is expected that the life expectancy of the scales would be considerable.

2. Wind Compensation:

None of the existing systems examined thus far possess this capability. All weighing would now have to be done inside a hangar to eliminate wind effects. There is some R & D presently being conducted in Germany by PAT Equipment on the effect of wind on static aircraft weighing. The consensus from the manufacturers that have been approached is that this is a very complicated problem (varying airfoil sections, varying angle of attacks, varying up-loads and down-loads in crosswind, etc....) and that the accuracy will be affected greatly. For example, a very quick computation of the lift generated by a Twin-Otter (DHC-6) wing at a wind speed of 10-15 knots produces a lift force of 300-750 lbs. This would not be an acceptable accuracy range.

Q: Does the weighing have to be done outside? If so would a wind speed limitation be acceptable (e.g. no weighing to be done if wind velocity is greater than 10 knots).

YES

Comments:

Most weighing would be done outside, therefore a wind limitation would be acceptable. If a serious overweight situation was suspected and the wind force too great, indoor facilities could be sought.

3. Weight of the System:

The original specification of 50 lbs as a maximum weight for the whole unit could only be achieved by using a load cell system. Since wheel pads are the only viable alternative and since the pads weigh roughly 50 lbs each, this results in the whole unit weighing aproximately 200 lbs (3 pads, 1 indicator/printer, cables, accessories, shock proof carrying case).

Q: Is a total unit weight of 200 lbs acceptable?

YES

Comments:

200 pounds would be the absolute maximum unit weight for the combined system.

4. Temperature Operating Range:

The majority of the models have an operating range revolving around -5°C as the lower limit. One model has a -18°C lower limit, while another one has a lower limit of -28°C. For the latter case, however, the indicator/printer operating limitations are much more restrictive (0°C). All the models without exception are capable of accepting temperatures up to +50°C.

Q: What is the lowest temperature limitation at which the scales are expected to operate at? How was -30°C temperature requirement arrived at?

-30 degrees Celsius was quoted as a "worst case scenario", however, it may be agreed upon that it is most unlikely that Inspectors will choose to weigh aircraft in temperatures of less than -10 degrees Celsius.

Comments:

5. Size of Pads:

Because of the physical size of the wheel pads themselves, the carrying case dimensions are most likely to be approximately 40W x 20L x 24H (inches).

Q: Do you foresee any problems in carrying this size case in an aircraft to a remote site? (It has been suggested that the case could stay inside the aircraft and that the components could be taken out one by one in order to facilitate handling).

YES, in some aircraft.

Comments:

A carrying case as described would present a problem loading and unloading in a Beach Baron, however should be no problem in King Air, Twin Otter or DC-3 aircraft.

Ontario Region has three Beach Barons and one Twin Otter.

6. **Pad Thickness:**

Only 3 wheel pad models meet the desired maximum thickness of approx. 1 inch. The other models have a typical thickness of 3 to 4 inches, and therefore, the use of entry ramps (typical, 9 degree slope) is required.

Q: Is the aircraft to be positioned onto the weigh scales on its own power? If so would a pad thickness of more than one inch be acceptable if entry ramps are provided? (It must be kept in mind that the necessity to carry ramps will increase the weight of the whole system considerably)?

The aircraft would normally be positioned on the scales under its own power. 4" scales would be unacceptable on account of the length of the ramp required to provide a 6 degree climb angle. Scales with a 21/2" rise require ramps of approximately 24", which would be acceptable provided total unit weight can be kept below 200 pounds.

Comments:

In the design of such scales, it should be kept in mind that when propellor driven aircraft are mounting the scales via a ramp, the propellor may pass close to the scale/ramp and we must ensure that the prop wash does not move the scale assembly causing damage to the aircraft and/or injury to persons nearby.

7. User Satisfaction

Q: Please indicate your level of satisfaction with the Haenni portable weigh scales now in use in the Ontario and Quebec regions. Please specify if the overall reliability, maintainability and performance of the system are meeting your expectations. Also an indication of any particular shortcomings would be appreciated.

Comments:

Some users found the Haenni portable weigh scales satisfactory, other than the ease of setting up and taking down and obtaining accurate readings in gusty wind conditions. Other users experienced problems in use on uneven or gravelled surfaces.

8. Weighing of Criteria

Q: Please indicate your appreciation of the following criteria to be used in the evaluation of the different systems available. Please indicate your preference by indicating the numbers 1 to 7 beside each criteria, 1 being the most important one.

#	Criteria
5	Capacity
7	Wind Compensation
4	Weight of System
6	Temperature Operating Range
3	Size of Pads
2	Thickness of Pads
1	Maintainability/Reliability

APPENDIX B

BINARY DECISION ANALYSIS
TECHNIQUE AND SAMPLE CALCULATIONS

BINARY DECISION ANALYSIS TECHNIQUE

Step 1 Identify the Important "Decision Criteria" or "Decision Variables"

This involves simply enumerating the factors, both quantitative and qualitative, which should be considered in selecting a weigh scale system from the perspective of a decision maker faced with a major capital expenditure. An effort is made to keep this list as short as possible without excluding any important variables, and to minimize the "double-counting" or duplication of variables. In other words, the criteria selected must be mutually exclusive and collectively exhaustive.

Step 2 Weighting the Decision Criteria

Having identified the major decision criteria, it is necessary to attach relative weights to each criterion, as they are not all equally important to the selection process. APS' binary decision analysis technique was used to establish the relative weights of the decision criteria.

The technique requires examining every possible pair of criteria, deciding which of the two criteria is the most important, and then assigning a 1 to the most important and 0 to the less important criterion. After every pair is evaluated the number of 1's received by each criterion is calculated to produce a "raw" total score. The highest scoring criterion is the most important. A simple mathematical transformation[1] is then performed to convert the raw scores into percentage weights or scores. A relative ranking can be assigned based on the percentage scores.

---

[1] Unity is first added to every raw score to ensure no zero scores are present and then each score is converted into a percentage figure.

Step 3 Evaluating Weigh Scale System Using the Decision Criteria

This step involves an assessment of each weigh scale model, to establish a ranking on the basis of ability to satisfy the criterion being considered. Again a binary decision analysis process is used. It involves examining the concepts in pairs, deciding which of the two concepts best meets the criterion being considered, and then assigning a 1 to the preferred type, and 0 to the less desirable type. After every pair of systems has been systematically analysed in this manner, a total is computed. The weigh scale systems with the highest score on a particular criterion is considered the best in fulfilling the demands of that criterion.

Step 4 Applying the Criteria Weights to the Evaluation Scores to Produce a Final Weighted Score for each System

In the previous step each system was evaluated on the basis of its ability to satisfy the criterion being considered without any regard for the relative importance or weight of the criterion. In the unweighted form, each criterion has equal value. For example, pad thickness cost is assumed to be just as important as reliability. Therefore, it is now necessary to weigh each system's score by the applicable criterion weight, so that the relative importance of each criterion can be incorporated. This is accomplished by multiplying the relative weights assigned to each of the criteria, by the scores assigned to weigh scales system for each criterion. This process produces a weighted score of each concept for each criterion considered. The total weighted score for each system is calculated by adding up the criteria weighted scores associated with a particular aircraft, and normalizing to unity.

It should be noted that the use of the binary decision analysis technique in this application requires such a large number of individual decisions to be made that any subjective biasing of the results by the analysis is highly improbable.

SAMPLE COMPUTATION OF BINARY ANALYSIS

Suppose there are three criteria (A, B, C)
and two alternatives (X, Y)

1) Weighting of Criteria

Criteria	Raw Score			Total Score	Transformed Score	Criteria Weight
A	1	1		2	3	50%
B	0		0	0	1	17%
C		0	1	1	2	33%
				3	6	100%

NOTES: - "A" is better than "B"
- "A" is better than "C"
- "C" is better than "B"
- Total Score is sum of Raw Scores
- Transformed Score is Total Score plus 1
- Weight is equal to $\frac{\text{Transformed Score}}{\text{Total Transformed Score}}$

2) Evaluation of Alternatives Using Criteria

a) For Criteria "A"

Alternative	Raw Score	Total Score	Transformed Score	Criteria Weight
X	1	1	2	67%
Y	0	0	1	33%
		1	3	100%

NOTES: - For Criteria "A", X is better than "Y"

b) For Criteria "B"

Alternative	Raw Score	Total Score	Transformed Score	Criteria Weight
X	0	0	1	33%
Y	1	1	2	67%
		1	3	100%

c) For Criteria "C"

Alternative	Raw Score	Total Score	Transformed Score	Criteria Weight
X	1	1	2	67%
Y	0	0	1	33%
		1	3	100%

3) **Final Scores & Ranking**

Alternatives	Score Per Criteria			Total Score
	A	B	C	
X	33.5	5.6	22.1	61.2
Y	16.5	11.4	10.9	38.8
				100.0

NOTE: - Cell "XA" = Criteria Weight "A" multiplied by
Alternative "X" for Criteria "A" divided by 100
= 50 multiplied by 67 divided by 100
Therefore, cell "XA" = 33.5

DEMONSTRATION AND PERFORMANCE EVALUATION OF SELECTED PORTABLE WEIGH SCALES FOR DETECTION OF OVERLOADED AIRCRAFT

PART 2

INCLUDES

PHASE I - SCALE TESTING AND CENTRE OF GRAVITY COMPENSATION

PREPARED FOR

TRANSPORTATION DEVELOPMENT CENTRE
RESEARCH AND DEVELOPMENT DIRECTORATE
POLICY AND COORDINATION GROUP
TRANSPORT CANADA

BY

AVIATION PLANNING SERVICES LTD

MAY, 1990

The contents of this report reflect the analysis and conclusions of Aviation Planning Services Limited and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

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In addition, the assistance from Mr. Peter Ayre, Innotech Aviation, and Mr. Russ Payson, Sky Services Ltd. is gratefully acknowledged.

EXECUTIVE SUMMARY

The objective of this study was to field test three weigh scales potentially meeting the requirements of Transport Canada Aviation Group, Enforcement and Legislation Branch (AARB) for detection of overloaded aircraft and recommend that which is most appropriate, continue research into providing enhanced weigh scale capabilities such as wind compensation and centre of gravity calculation, and recommend a suitable approach for detecting overloaded seaplanes, including float planes.

The Transportation Development Centre (TDC), contracted this work on behalf of Enforcement and Legislation of Transport Canada's Aviation Group (TCAG). The study was performed in response to recommendations made by Aviation Planning Services and contained in the February, 1989 report: "Portable Weigh Scales for Detection of Overloaded Aircraft".

The methodology involved reviewing all previous manufacturers' literature, designing, and undertaking practical performance evaluation tests of the three scales manufactured by Haenni, Intercomp and the PAT Equipment corporation, followed by an analysis of the results. The performance evaluation included:

- Training of APS personnel by the manufacturers' representatives. This allowed an assessment of the complexity of the equipment for pedagogic purposes

- Conducting field trials by weighing a selection of actual aircraft with the portable scales and a benchmark scale to test accuracy

- Deriving a set of decision criteria and using these criteria to determine a relative preference among the three systems.

The results of the performance evaluation indicated a selection of the scales manufactured by Haenni, Switzerland. The main advantages of these scales were pad height and weight and the ease with which they are operated. The PAT Equipment Corporation scales also performed very well although the operation was more complicated and the pads themselves were heavier and thicker than the Haenni scales. The Intercomp system had some positive aspects, particularly in regards to the CPU/printer, but generally did not perform up to specifications.

The final aspect of this study dealt with a procedure for deriving the centre of gravity. The aircraft's centre of gravity with respect to the nose wheel is easily obtainable given the weights on each wheel and all relevant distances. All three systems tested were capable of being programmed such that centre of gravity could become part of the standard output.

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1. INTRODUCTION

At the request of the Transportation Development Centre (TDC) of Transport Canada, Aviation Planning Services Ltd. (APS) undertook the evaluation of selected portable weigh scales which could be used to detect overloaded aircraft.

This project was a follow-up to another study undertaken by APS. The previous study identified equipment and key parameters. The report was submitted in February 1989 with the recommendation that further study be considered in three areas in view of the absence of sufficient field experience. These were:

- Scale testing and centre of gravity calculation;
- Wind effects compensation;
- Overloaded seaplane detection.

This report deals with the first phase of the study - that is: Scale testing and centre of gravity calculation.

1.1 Problem Definition

The portable weigh scales studied in the previous report were not in sufficient use in the aviation industry to properly evaluate reliability and user satisfaction. Only one model (manufactured by Haenni) was in use in the industry and the lack of competitive data did not allow for an overall recommendation to be made. The three scales which best met the criteria originally established by Transport Canada and subsequently modified by APS in conjunction with Transport Canada were manufactured by Haenni, Intercomp and the PAT Equipment Corporation. It was therefore required to develop and implement a methodology and test program which would evaluate the three weighing systems and provide stronger

recommendations based on scientific testing with respect to the most suitable scales for Transport Canada.

1.2 Methodology

The study methodology followed, in general, the presentation format of this report and is summarized by the following elements:

i) Review of the previous report as well as the manufacturers' supplied documentation.

ii) Contact with the manufacturers of the three weigh scales and procurement of both equipment for testing and operational training of APS engineers in the use of their weigh scales.

iii) Location of a test site in compliance with the criterion of a zero wind, sheltered environment.

iv) Securing a number of test aircraft within the required weight class (below 65,000 pounds).

v) Securing benchmark scales to validate the readings of the portable scales.

vi) Field Testing by APS. This involved:

a) Calibration of the portable scales with reference to a benchmark (non-portable) scale.
b) Weighing all test aircraft with portable scales;
c) Measuring aircraft ground contact point dimensions for use in centre of gravity (C of G) calculations;
d) Videotaping all procedures;

e) Photographing experimental set-up, aircraft, hangar and personnel.

f) Review of aircraft weight and balance documents.

vii) Analysis of the data and evaluation of the scales.

viii) Computation of aircraft centres of gravity and correlation with weight and balance statements in order to develop the procedure for the generation of universal C of G tables or a simple model.

ix) Identification of scales which, at the present time, seem the most appropriate for Transport Canada applications.

1.3. Report Statement

This report contains the details of the work performed by APS for the internal use of Transport Canada. While every effort has been made to obtain the most up-to-date and accurate data possible, the consultants disclaim any responsibility for misrepresentations by the manufacturers or issues beyond the control of APS.

2. SELECTION CRITERIA AND PERFORMANCE REQUIREMENTS

The report of February 1989 presented seven criteria which were used to evaluate portable weigh scales. These seven criteria were:

i) maintainability/reliability;
ii) pad thickness;
iii) pad size;
iv) weight;
v) system capacity;
vi) operating temperature range; and
vii) wind compensation.

It should be noted that the study environment for the first report was quite theoretical and very limited practical field experience existed, especially in terms of aircraft weighing. Consequently, as the current study progressed, first hand experience by TC and APS personnel motivated a revision to the criteria by which one scale would be recommended. In particular, "pad size" was modified to account for factors other than minimum size. System capacity was no longer an issue as all candidate scales met the capacity criterion. Operating temperature range was also deleted in view of TC specification of human factors (difficulty with low temperature operatives). Finally, wind compensation was transferred to a scale independent analytic study, to be conducted in this project.

Three new criteria were introduced. These were, ease of operation, accuracy and precision, and software capability. The complete list of criteria, their descriptions, and the measurement technique are provided below:

2.1 Wheel Pad Thickness

This remains a primary concern as the ability of enforcement officers to conduct a weighing depends directly on the ability of the pilot to load the aircraft on the pads. This parameter was objective and provided by the manufacturers.

2.2 Ease of Operation

This is a parameter which takes into account setting up the equipment and obtaining results in a relatively rapid manner. Specific aspects include cable connections, power supplies and the amount of "button pushing" which must occur to obtain readings. It was measured subjectively by three APS engineers.

2.3 Pad and System Weight

The weights of the pads are a factor in how easy the systems are to transport, position and re-position. This parameter was objective and provided by the manufacturers.

2.4 Durability/Maintainability

The fact that the pads may be used frequently at smaller airports with variable surface conditions necessitated the inclusion of durability as a factor. Uneven weighing surfaces may be common at these airports and the weighing system must be able to withstand the uneven stresses placed upon them. Should any breakdown of the system occur, it is important that there exist a manufacturer approved service center to repair and/or replace non-functional equipment. This representative should be stationed in Canada to avoid border/custom's delays.

Therefore, measurements of this parameter were based on APS professional judgement and evaluation of manufacturers' claims.

2.5 Accuracy and Precision

It is expected that all the weighing systems will produce results which fall within their documented range of accuracy. However, some systems are more accurate than others and some can reproduce results better than others, both of which are important considerations. Also, a correlation between published accuracy and tested accuracy may be useful in any prosecutions or in the event of legal challenges. Therefore, measurements were objective with statistical analysis as the data processing technique.

2.6 Software Capability

For report and documentation purposes, it would be preferable if the operator could record the output internally for later use. The ability to properly program the software could immediately give other useful information to the operator, such as centre of gravity. Also, by retrieving data from a pre-programmed data bank, the operator can determine how overweight the aircraft is and whether or not the aircraft's centre of gravity falls within acceptable limits. This criterion was evaluated on the basis of manufacturer's specifications.

2.7 Weighing Surface Area

Given the fact that all three products were deemed small enough to be defined as "portable" during the first study, it was decided here to make the available weighing surface area a criterion. The pad surface area usable

for weighing aircraft is important for two reasons. Obviously, the first is that it enables larger aircraft to be weighed on the pads. The second is that it allows smaller aircraft to be weighed despite the fact that the pads may not be properly aligned. The measurements along this criterion were objective and provided by the manufacturers.

It may be noted that the above criteria contain both easily quantifiable and non-quantifiable elements. Subjective elements are the most problematic from the point of view of defensibility. However, APS has attempted to maximize defensibility by assigning three engineers of varying levels of education and experience to the training and field testing. Each of them documented their subjective evaluations independently, followed by discussions with TC personnel to achieve consensus.

A note should also be made of the absence of "cost" as a criterion for selection. The consultants believe that in matters of legislation, cost should be secondary to a defensible technical decision. Furthermore, the costs would be a function of direct negotiations between the suppliers and TC and the number of units ordered. Therefore, cost was not a criterion.

3. PRODUCT DESCRIPTIONS

The three weighing systems studied in this analysis all have elements which differentiate them from each other, either in their physical description or in their method of operation. This section will provide the physical description and explain the operation of the three systems. The explanation is a product of both the instruction received from the individual manufacturers and of the APS experience during the field trials of this project.

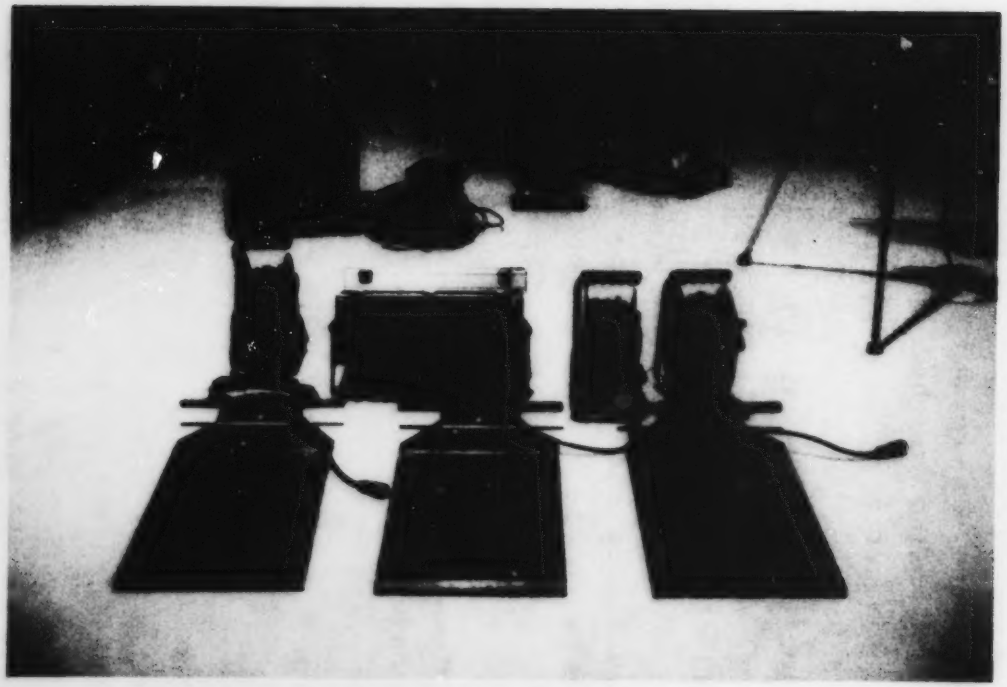
3.1 Haenni

Of the three systems tested, the Haenni system is the only one which works on the principal of hydraulics. When weight is applied to the pads, hydraulic fluid is forced into a measurement housing which contains the electronics. The electronic signal resulting from the fluid displacement is sent to the central unit which calculates the weight.

The Haenni system is composed of three weigh pads, a microprocessor based central unit and connection cables. The system is shown in Plate 3.1. The pads are thin (15 m or 0.6 in. high) and have a weighing surface area of 2.56 square feet. The weight of each pad is 14.5 kg (32 lb). The test pads had no local readout although such models are available. The electronics of each pad is enclosed in a shielded housing on one side of the pad. The central unit is contained in a shielded carrying case and includes a small printer, an LCD display, and some function keys. The pads are connected directly to the central unit through cables which have their own winding wheel case. The entire system is powered by a small 12 volt power supply. For transportation the pads have their own boxes. The central unit and cables are carried

PLATE 3.1

HAENNI SYSTEM



Source: APS Photo

individually. The National Bureau of Standards Handbook 44 (NBS H44) accuracy specifications are as follows:

± 70 lb (0 ... 2500 lb)
± 140 lb (2500 ... 10000 lb)
± 210 lb (10000 ... 20000 lb).

These accuracies are on a per pad basis, therefore heavy aircraft being weighed on three pads will have a cumulative error of ± 630 lb (1 to 2 percent).

Setting up the Haenni system is not difficult. The cables attach easily and securely, the pads are relatively lightweight and the central unit can be placed on the ground. Once the set up is complete, the aircraft weight limits are entered into the system, the pads are zeroed with the touch of a button and the aircraft is loaded on. Because of their thinness, loading the aircraft is simple. One concern voiced by the aircraft operators was the fact that although they are low, the pads have a sharp lip over which the aircraft must roll. There was some concern about perhaps damaging high pressure tires. The weights themselves are obtained and printed by pushing two keys ("weigh" and "print").

Another concern lies in the durability aspect of the Haenni scales. The manufacturer stated that the scales may bend slightly under heavy loads on very uneven surfaces. However, if the pads should bend, then the operator could simply bend them back with no loss of accuracy. The consultants do not fully accept this claim. However, in any practical applications, the type of surface on which aircraft are weighed is a controllable variable. Asphalt, level turf or smooth gravel areas can be found at any airport, thereby, rendering this concern a non-issue.

3.2 Intercomp

The Intercomp system uses load cells to obtain its weights. In the weigh pads, four load cells are arranged in a rectangle. The weight applied is calculated by summing the output from strain gauges in the load cells. These strain gauges are embedded in the load cells, which are housed between two outer plates.

The complete Intercomp system consists of three weigh pads, cables, a switching box, and a small portable computer/printer. The Intercomp system is shown in Plate 3.2.

The pads presented the highest profile (1.7 inches) of the three systems reviewed. The active weighing surface is published to be 2.3 square feet and each pad weighs 48 pounds. Each pad had a shielded LCD display with some function buttons for local readings or display testing. Each pad is connected to the central computer through cables and a switching box.

The central computer is an off-the-shelf portable unit (Epson) with a standard serial port for connection to other computers. The weights are obtained via a small program which is loaded onto the computer.

The entire system comes with a carrying case the size of a steamer trunk. This case offers excellent protection to the equipment. Due to the height of the pads themselves, it may be preferable to include small ramps which would make loading the aircraft significantly easier. The system operates by rechargeable AA batteries with a life of approximately eight hours between charges. The published system accuracy is ± 1%.

PLATE 3.2

INTERCOMP SYSTEM

Source: APS Photo

The system is as easy to set up as the Haenni system. The only difference in its operation is the use of a switching box. The pad weights are obtained individually by manipulating the switch on the box. This results in a greater number of steps which must by performed before the actual total weight can be obtained. The CPU is small and light enough so that it does not need to be set down, although the existence of the switching box inhibits the operator from freely moving around.

3.3 PAT Equipment

The PAT system also uses strain gauges in the calculation of its weights. The difference between the PAT system and the Intercomp system is that the gauges of the PAT system are integrated into its aluminum alloy construction which should allow weights to be measured accurately anywhere on the weighing surface.

The PAT system used in the testing comprised of four weigh pads, connecting cables, a switching box and the central unit. The PAT system is shown in Plate 3.3. It may be noted that there were four pads used in this study. The reason for this was the manufacturer's available configuration at the time of testing. This was the configuration used by the manufacturer for truck weighing, a function for which this system was originally designed. It was stated by the manufacturer that reconfiguration of the system with only three pads was a simple transformation. However, for our experiments, four pads were used. The aircraft wheels were placed on three pads. A dummy weight was placed on the redundant pad. Each pad provided an independent weight reading. Therefore, in the analysis, the dummy weight was discarded without any loss of accuracy or validity.

PLATE 3.3

PAT SYSTEM

Source: APS Photo

The pads are 1.2 inches high with an active weighing surface area of 2.3 square feet. The individual pads weigh marginally under 50 pounds (22.5 kg). The scales have a protected LCD display which registers individual weights. The cables are simple slide-in connection cables although there was some problem with cable and/or connection failure during testing.

The CPU/printer is in a protective case which can be positioned anywhere during weighing. The system is powered by a 12 volt power supply. The individual pads can operate on their own as they contain rechargeable batteries.

The system has NBS H44 accuracy specifications of:

± 55 lb (0 ... 5500 lb)
± 110 lb (5500 ... 20000 lb).

These are on a per pad basis. A heavy aircraft weighed on three pads could therefore have a maximum cumulative 330 pound error (½ to 2 percent).

As with the other two systems, there is very little involved with setting up the PAT scales. The cables and connection problems were present although there could perhaps be some modifications done on the system to alleviate this. The weighing procedure itself is a little more involved. As the system was originally programmed, the operation involved inputting axle parameters and weight limits. It is expected that this too, could be reprogrammed into a slightly simpler procedure. The switching box is another element which requires attention (in a manner similar to the Intercomp system).

The PAT scales appear to be very durable. The manufacturer demonstrated his confidence in his system by dropping a pad from an angle of 45 degrees onto a concrete floor. Another evidence of durability is the fact that the scales were shipped without any protective packaging whatsoever and still functioned well.

It should be noted that, *ceteris paribus*, some aspects of the systems which were observed to be unsatisfactory could be modified in order to make them less so. During the analysis, the distinction between improvable and non-improvable elements was maintained.

4. EXPERIMENTATION

This section describes the training, calibration and field trials of the weigh scales with real aircraft.

4.1 Training

The experimentation phase consisted of three distinct activities. Firstly, APS engineers (3) were trained by the manufacturers' representatives. Secondly, the scales were calibrated against a benchmark scale. Thirdly, actual aircraft were sequentially weighed with each of the scales.

It was necessary for all the consultants to become proficient in the operation of each weighing system in order that the subjective aspects of the analysis could be assessed. APS personnel were trained by the manufacturers on the 20th and 21st of February, 1990.

4.2 Calibration

Calibration implied measurements of the accuracies of the portable scales in comparison to measurements taken with a non-portable system established as a benchmark scale.

The operational difference between the benchmark scale and the portable scales involved the requirement to jack-up the aircraft for weighing with the benchmark scale. In addition, the benchmark scale was in regular use at Innotech Aviation for aircraft weighings and calibrated regularly. Therefore, it's accuracy was assumed to be within the required limits.

The benchmark scales were manufactured by General Electrodynamics Corporation; model GEC145 (serial number

13240), calibrated in June 1989. The load cells accuracy, ± 0.1%, implied a maximum error of 30 lb for a 30,000 lb weight.

Calibration was done by weighing one aircraft on the benchmark and all portable scales[1]. The aircraft selected was the Canadair Challenger. The selection was based strictly on the availability of an aircraft for test purposes[2].

Calibration was done on the day immediately following training and was conducted in the presence of the manufacturer's representatives. This presence was important in case their assistance was required as well as having them witness both the procedure followed and the manner in which the entire event was handled. It was requested that the manufacturers not be present on the second day of field trials.

4.3 Field Trials

The first day of trials involved three aircraft: a Canadair Challenger, a Cessna Conquest, and a Piper Cheyenne. As suggested earlier, the Challenger served the dual purpose of providing calibration data as well as a test aircraft for the portable weigh scales. Plate 4.1 shows the Challenger jacked up on the GEC load cells. Day two of the trials involved weighing another Challenger, a Merlin Metroliner and an HS 125.

The experimental set up initially involved three separate aircraft, one each on the three candidate scales.

---

1 Budget constraints limited this calibration to only one aircraft.

2 Coordinated by courtesy of Sky Service Ltd., Dorval.

PLATE 4.1

CANADAIR CHALLENGER
JACKED UP ON GEC LOAD CELLS

Source: APS Photo

Readings were sequentially taken on the three aircraft-scale set ups. Upon completion of one run of readings, the aircraft-scale combinations were permutated and readings taken again. This operation was conducted three times to secure readings for each aircraft on each candidate scale.

Plate 4.2 shows the Piper Cheyenne on the Haenni scales during this phase of the testing. To increase the number of data points acquired in the time available, the procedure was revised midway through the first day of testing. Each aircraft was weighed repeatedly on all three scales by transferring the aircraft off one scale directly onto another. The Hawker Siddeley 125 is shown in Plate 4.3 with the scales set up in this manner. The set up times were approximately 10 to 15 minutes, for a two person crew. This time did not include the actual towing of the aircraft onto the scales. It was originally expected that the ground personnel would be able to manually load the aircraft. It became apparent that for any aircraft weighing in excess of six or seven thousand pounds it would be difficult to do so, and for an aircraft weighing more than ten or twelve thousand pounds, it would be virtually impossible. Therefore, it became necessary to load all aircraft using a tow bar and a mule (tractor).

Despite the fact that all three systems had capacities of 20,000 lb per pad, the manner in which weight is distributed between nose wheel and main wheels on most aircraft would make weighing any aircraft above 48,000[1] pounds impossible with only three pads. It is normally

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[1] The 48,000 lb limit was established empirically for the test aircraft although as a general rule, it would depend on the ratio of main wheels to nose wheel loading.

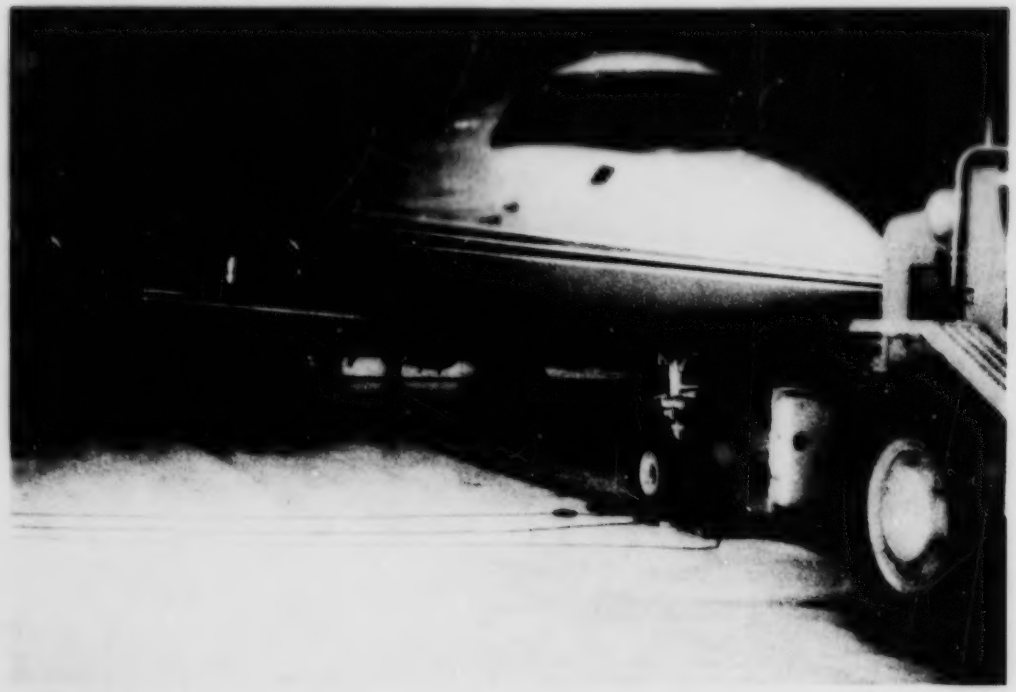
PLATE 4.2

PIPER CHEYENNE ON HAENNI SYSTEM

Source: APS Photo

PLATE 4.3

HAWKER SIDDLEY 125 ON HAENNI SCALES



Source: APS Photo

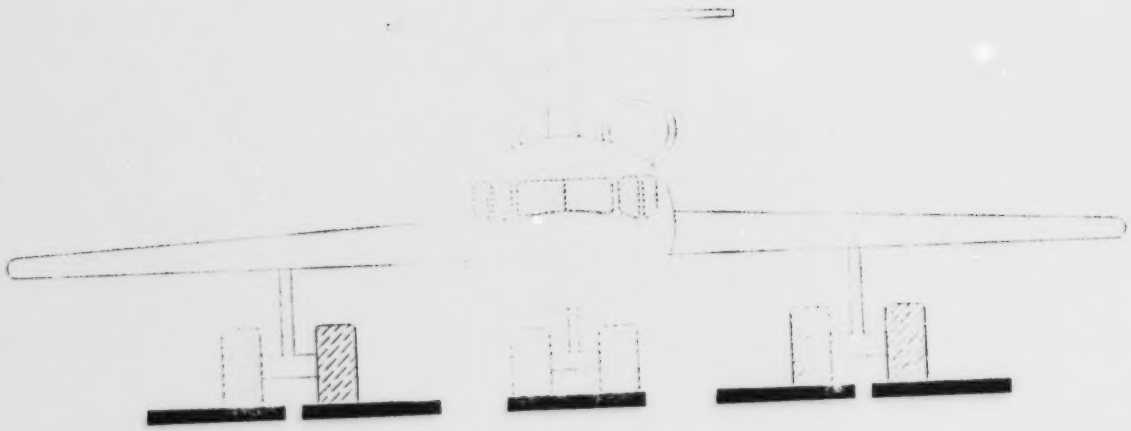
the case that aircraft of higher weights are designed with dual undercarriage. This implies that heavier aircraft could be weighed by using two pads per main gear and one for the nose wheels as shown in Figure 4.1. However, this would require five pads, which would increase the weighing system weight by 67% (from 3 to 5 pads).

The final aspect of the field trials involved measurement of the aircraft weight vectors, that is, weights and points of application. These dimensions were the wheel track and the base, which is the perpendicular distance from the nose wheel to the main gear axis. Other dimensions, such as wheel thickness were also taken to allow the calculation of the actual distances between weighing points. Although dimensions were given on the aircraft weight and balance documents and, as a result, did not need to be physically measured, it was considered prudent to secure the data for future reference. It was noted, however, that the difference between the measured values and the values given by the weight and balance sheets were negligible.

The location and magnitude of weight vectors data was intended for use in the determination of the C of G of the aircraft and the ultimate development of tables and procedures to convert arbitrary three point weight vector readings to a C of G position. The details of this part of the study are presented in section 6.

The summary results of the weight experimentation, are presented in Table 4.1, while samples of the raw data forms are attached as Appendix A.

FIGURE 4.1
FIVE PAD WEIGHING SET UP



Source: APS Illustration

TABLE 4.1
SUMMARY OF TOTAL WEIGHTS
FIELD TRIALS

DAY	AIRCRAFT TYPE	TRIAL	SCALES			BENCHMARK
			HAENNI	INTERCOMP	PAT	
			WEIGHT (LB)	WEIGHT (LB)	WEIGHT (LB)	WEIGHT (LB)
22 FEB	CHALLENGER A	1	28,702	26,850	28,880	28,990
		2	28,583	26,850	29,000	28,960
	CONQUEST	1	7,930	7,600	8,000	
	CHEYENNE	1	8,781	8,300	8,920	
		2	8,768	8,450	8,880	
		3	8,746	8,400	8,960	
23 FEB	CHALLENGER B	1	29,452	27,600	29,560	
		2	29,496	27,250	29,620	
	MERLIN	1	8,920	8,700	9,080	
		2	8,882	-	9,080	
	HS125	1	18,025	17,750	18,320	
		2	17,987	17,600	18,280	

SOURCE: AVIATION PLANNING SERVICES

It can be noted from Table 4.1 that the number of data points were limited[1]. However, there does appear to be some consistency in the results. For example, PAT weights are consistently higher than the weights recorded by the other scales, while Intercomp was substantially lower than the other two.

A review of these quantitative results and an evaluation of the qualitative factors formed the input to the selection process, which is discussed in the next section of this report.

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1 Due to budget and time constraints.

5. SELECTION PROCESS

In Section 2, the consultants defined and described a number of criteria which would form the basis of selection of one of the three candidate scales. In Sections 3 and 4, qualitative and quantitative data was acquired on all of the scales to allow justifiable comparisons. This section describes a decision model used for making complex selections.

The model is the Binary Decision Model (BDM). It integrates relative criteria and product preference data in a simple process so that the decision maker is not confronted with vast amounts of data at one time. Details of the application of the model using an example are shown in Appendix B, while this section presents the application to the current project.

It may be noted that the objective of this exercise is to obtain a relative score for each of the three products while accounting for all of the criteria.

5.1 Binary Decision Model Overview

BDM was developed by Westinghouse and modified by Aviation Planning Services. It is essentially a systematic process for subdividing a complex array of decisions into decisions involving only two choices at a time. These individual decisions are then aggregated to give overall results.

The important aspect of the binary decision analysis technique is the weighting of the individual criteria and then positioning of the products along each criteria.

5.2 Criteria Weighting

The seven criteria identified in Section 2 were compared

in pairs to determine their relative importance. The comparisons are summarized in Table 5.1, where a comparison between two criteria is displayed as a "1" for the more favourable criterion and "0" for the other. Therefore, each column of data represents an independent comparison of two different criteria. The frequency count of favourable outcomes for each criterion is taken as a measure of its relative importance.

The "scoring" of the criteria was based on the judgement of TC personnel coupled with that of the APS engineers. The combined results shown in Table 5.1 indicate that Pad Height was considered the most important criteria with a relative weight of 25%. Following this, "Ease of Operation" had a weight of 21%. "Pad and System Weight" ranked third, "Durability/Maintainability" ranked fourth, "Accuracy and Precision" ranked fifth, "Software Capability" as sixth and "Weighing Surface Area" in seventh place.

5.3 Product Scores/Criterion Analysis

The three products were compared in pairs along each criterion. Sections 5.3.1 through 5.3.7 present the rationale behind the scoring of the products along the individual criteria.

5.3.1 Pad Thickness

The results are due solely to the physical dimensions of the weigh pads. The Maenni pads are the thinnest and the Intercomp pads are the thickest.

TABLE 5.1

CRITERIA WEIGHTING EXERCISE

CRITERION	RAW SCORE	TOTAL SCORE	TRANSFORMED SCORE	CRITERIA WEIGHT
ACCURACY AND PRECISION	0 0 0 1 1 0	2	3	10.7
DURABILITY/MAINTAINABLITY	1 0 0 1 1 0	3	4	14.3
EASE OF OPERATION	1 1 1 1 1 0	5	6	21.4
PAD AND SYSTEM WEIGHT	1 1 0 1 1 0	4	5	17.9
SOFTWARE CAPABILITY	0 0 0 0 1 0	1	2	7.1
WEIGHING SURFACE AREA	0 0 0 0 0 0	0	1	3.6
WHEEL PAD THICKNESS	1 1 1 1 1 1	6	7	25.0
TOTAL		21	28	100.0

Notes: Transformed score = Total Raw Score + 1
Criterion weight = (Transformed Score)/(Total of Transformed Scores)

Source: Aviation Planning Services Analysis

5.3.2 **Ease of Operation**

During the field trials, the consultants found that the Haenni scales required the least amount of effort to operate while the PAT Equipment scales required the most. This was mainly due to the cables required for the PAT system which were unreliable. In addition, the existence of the switching box made the PAT scales less "user friendly" than the Haenni scales. The Intercomp system also had a good cable system although the system included a switching box needed to record the weights on the various pads.

5.3.3 **Pad Weight**

The thin Haenni pads were also the lightest while the PAT and the Intercomp pads had approximately equivalent weights.

5.3.4 **Durability/Maintainability**

The major concern with the Haenni pads is in their ability to withstand use and abuse. The minimal thickness may lead to some deformation on uneven surfaces. Another concern is the relative position of the measurement housing on the edge of the pad. There would be a risk of aircraft tire overrun and potential damage to the system. In contrast to the Haenni system, the PAT system was considered extremely durable. The Intercomp scale was judged less durable than the PAT scales. The specific concern within the Intercomp system would be the ruggedness of the computer which would not

withstand any misuse.

In terms of maintainability, although all three systems are manufactured outside Canada, all have Canadian service centres who maintain their products. Estimates of in house maintainability by TC technicians were not available at this time.

5.3.5 **Accuracy/Precision**

Both the PAT and Haenni scales consistently gave results within their published specifications. The Intercomp scales consistently gave results substantially lower than the other two products and were about 2,000 lbs (7.3%) below the benchmark value for the Challenger. In terms of accuracy as measured against the benchmark weight of the Challenger, the PAT scales differed by just over 0.1%; the Haenni by 1.1%. This formed the basis of ranking the scales along this criterion.

5.3.6 **Software**

Although there were some differences in the programming of each weighing system, it was accepted that all three manufacturers would be able to tailor their system to the needs of the client. The advantage of the Intercomp system was that its "off the shelf" computer could be attached to any other PC using a standard serial cable. This would be advantageous for data collection and report purposes.

5.3.7 Weighing Surface Area

This is another purely physical consideration with one exception. It was noticed, during the weighing of the Challenger, that the Intercomp plate was buckling up and the value was substantially off the benchmark value. The most probable reason for the plate buckling is that the load was concentrated outside of the area delineated by the four load cells although still within the theoretically active weighing area. The Intercomp scales were therefore penalized in this comparison.

5.4 Individual Product Scores

The cumulative scores of each of the three scales along the seven criteria are presented in Table 5.2. The table shows both the results of the individual comparisons as well as the relative scores in percentage terms for the three products along each criterion.

5.5 Composite Product Scores

The final step in the binary analysis was the combination of all the relative scores with the criterion weights. This determined an overall relative ranking of the three systems. The results, weighted by criterion scores and combined into a single value, are presented in Table 5.3.

From the results of the binary analysis it is evident that, although each system has its own merits, the Haenni system would seem to conform most to the requirements of Transport Canada by a relatively large margin.

TABLE 5.2

DEVELOPMENT OF INDIVIDUAL PRODUCT SCORES

	INDIVIDUAL PRODUCT SCORES *						
	PAD THICKNESS	EASE OF OPERATION	PAD WEIGHT	DURABILITY MAINT.	ACCURACY PRECISION	SOFTWARE CAPABILITY	WEIGHING SURFACE
HAENNI	1 1	1 1	1 1	0 0	1 0	0 .5	1 1
INTERCOMP	0 0	0 .5	0 .5	1 0	0 0	1 1	0 0
PAT	0 1	0 .5	0 .5	1 1	1 1	.5 0	0 1
	FINAL SCORES **						
HAENNI	50	50	50	17	33	25	50
INTERCOMP	17	25	25	33	17	50	17
PAT	33	25	25	50	50	25	33
TOTAL	100	100	100	100	100	100	100

* Individual product scores are either 0 or 1, unless they are equal, in which case score is .5.

** Final score for each product for each criterion is equal to the sum of the individual scores plus 1 divided by the sum of the total scores with the result being put into percentage terms. For example, for pad weight, the scores are (2+1),(0+1) and (1+1) for the Haenni, Intercomp and PAT scales respectively, giving a total score of 6. The final score for Haenni under this criterion, is therefore (2+1)/6 or 50 percent.

Source: Aviation Planning Services Analysis

TABLE 5.3
COMPOSITE PRODUCT SCORES AND RELATIVE RANKING

SCALES	SCORE PER CRITERION							TOTAL SCORE
	1	2	3	4	5	6	7	
HAENNI	12.5	10.7	8.9	2.4	3.6	1.8	1.8	41.7
INTERCOMP	4.2	5.4	4.5	4.8	1.8	3.6	0.6	24.7
PAT	8.3	5.4	4.5	7.1	5.4	1.8	1.2	33.6

CRITERIA INDEX:
1. Pad Height
2. Ease of Operation
3. Pad Weight
4. Durability/Maintainabiltiy
5. Accuracy and Precision
6. Software Capability
7. Weighing Surface Area

NOTES: Composite product score per criterion =
individual product score per criterion x criterion weight / 100

EXAMPLE: Haenni for Pad Height
composite score = 50 x 25. / 100 = 12.5

Source: Aviation Planning Services Analysis

5.6 System Cost

Although the cost of the system was deemed not to be a significant factor in the selection of the weighing system, quotes were obtained from the manufacturers and are presented here. It should be noted that in contrast to the first study, these quotes were obtained from the manufacturers themselves and not their local representatives. This led to a significant drop in the price of at least one system.

The quoted costs were:

- Haenni: $24,500 CDN
- PAT: $23,500 CDN
- Intercomp: $21,000 CDN[1]

All of the above were FOB Montreal exclusive of sales taxes.

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[1] Intercomp price as given in previous report, no updated costs supplied.

6. CENTRE OF GRAVITY

As part of this study, an analytic technique for the determination of the C of G in the field, was developed. This involved a mathematical model, which was tested after the field trials of the scales.

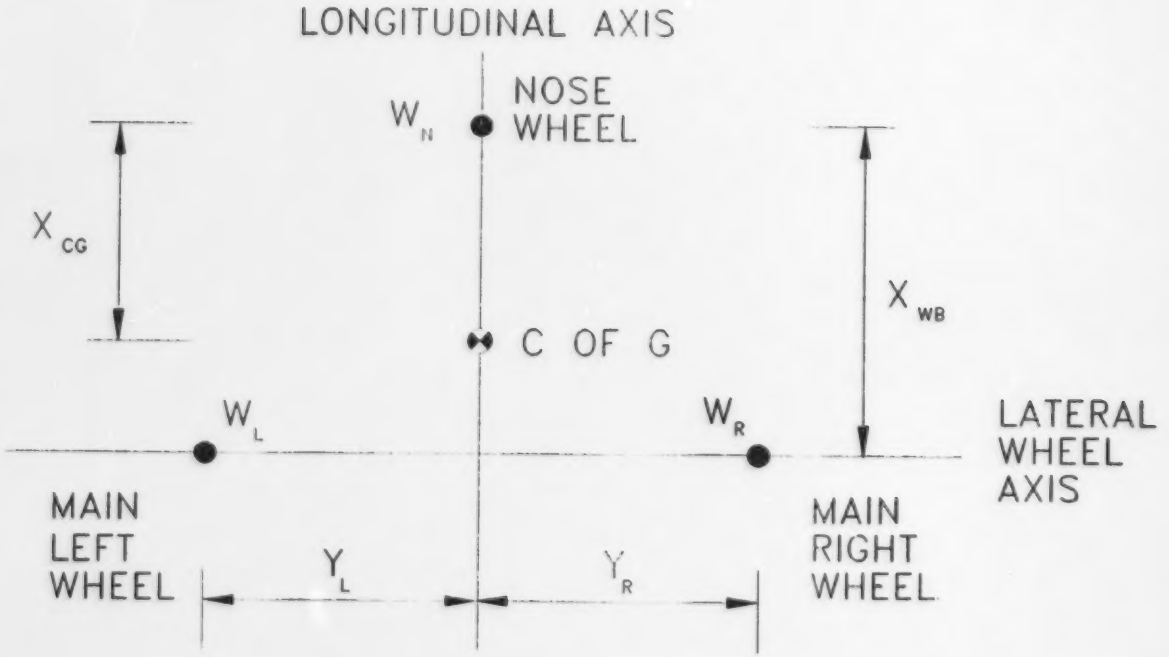
As suggested earlier, the input data to this model was the set of weight vectors i.e., the weights on each wheel pad and the locations of the application points measured as distances between the pads. The C of G calculations were made with this model. The model results could have been correlated with the automatic readout had this been available. In its absence, these were compared with the weight and balance documentation of the aircraft. This section presents the model and the process of correlation.

6.1 Model Development

It may be noted that the set of weight vectors have application points which form (ideally) an isosceles triangle, where the apexes correspond to the centre of the wheels' footprints.

Figure 6.1 shows the geometry and notation used in this report. "W" corresponds to weight, "X" the distance along the longitudinal axis, and "Y" the distance along the main wheel axis. Subscripts N, L, R refer to nose, left and right (wheels) respectively while WB refers to the wheel base, T to total, and CG to the centre of gravity. The interest in the C of G position is strictly along the longitudinal axis. Therefore, for modelling purposes, W_L and W_R may be composed to provide an effective main wheel weight vector, W_M, at the intersection of the longitudinal and lateral wheel axes.

FIGURE 6.1
GEOMETRY OF WEIGHT VECTORS



Source: APS Illustration

This composition simplifies the C of G calculation considerably as only a one dimensional problem remains. This is illustrated in Figure 6.2. The position of the C of G with respect to the nose wheel is computed through an equilibrium of the moments. Therefore, taking moments about the nose wheel,

$$W_M \; X_{WB} = W_T \; X_{CG} \quad , \text{ and}$$

$$X_{CG} = W_M \; X_{WB} \; / \; W_T = (W_L + W_R) \; X_{WB} \; / \; W_T$$

A more sophisticated model would position the C of G in two dimensions i.e., laterally as well as longitudinally. The reference points for the advanced model are shown in Figure 6.3. The formulae are developed below by balancing moments about the centre of gravity.

<u>X-centre of gravity:</u> (Positive Aft)

i) $W_L \; (X_L - X_{CG}) + W_R \; (X_R - X_{CG}) = W_N \; X_{CG}$;

ii) $W_L \; X_L + W_R \; X_R = X_{CG} \; (W_N + W_L + W_R)$;

iii) $X_{CG} = (W_L \; X_L + W_R \; X_R) \; / \; W_T$;

where $W_T = W_L + W_R + W_N$.

<u>Y-centre of gravity:</u> (Positive Right)

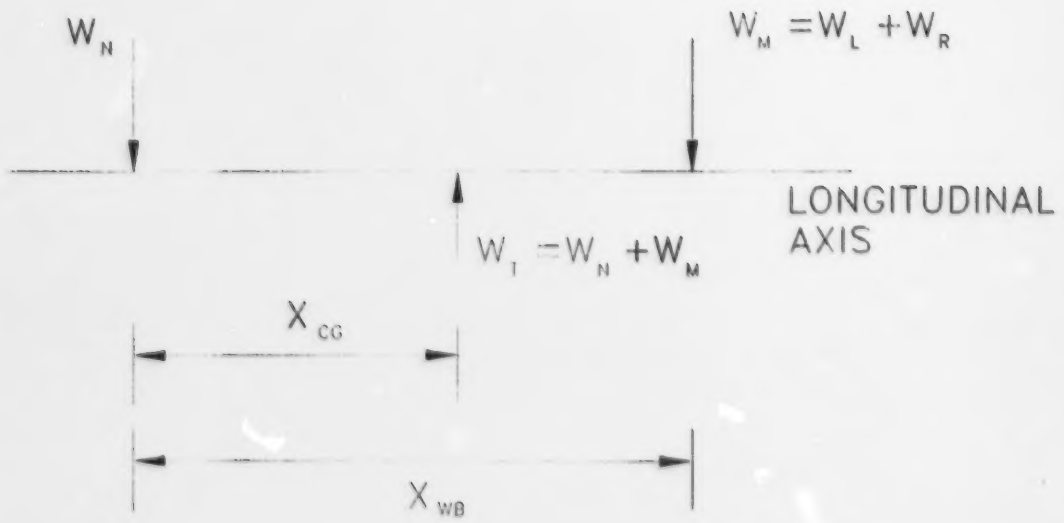
i) $W_R \; (Y_R - Y_{CG}) = W_L \; (Y_L + Y_{CG}) + W_N \; Y_{CG}$;

ii) $W_R \; X_R - W_L \; X_L = Y_{CG} \; (W_N + W_L + W_R)$;

iii) $Y_{CG} = (W_R \; Y_R - W_L \; Y_L) \; / \; W_T$;

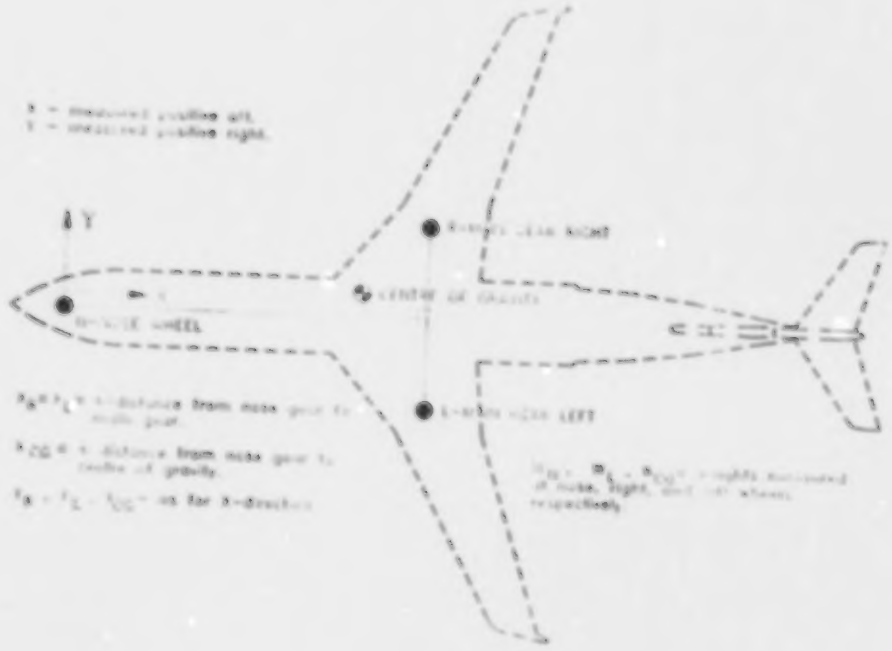
where $W_T = W_L + W_R + W_N$.

FIGURE 6.2
SIMPLIFIED GEOMETRY OF WEIGHT VECTORS



Source: APS Illustration

FIGURE 6.3
ADVANCED MODEL GEOMETRY



Source: AFS Illustration

The centres of gravity, as calculated, are tabulated in Table 6.1.

6.2 Weigh Pad Induced Error

Given the accuracy specifications of the products, it is possible to calculate the margin of error for the centre of gravity calculations. Although the Y-centre of gravity is displayed in Table 6.1, most weight and balance sheets do not contain this information. Therefore, this section will deal only with the potential errors related to the X-centre of gravity (the APS one dimensional model).

The forward and aft limits of the calculated centre of gravity range can be determined by using the extrema from the scale accuracy specifications. For example, consider the first Haenni weighing of Challenger A. The weights for the nose wheel, main left wheel and main right wheel were 2205 lb, 13307 lb, and 13190 lb, respectively. As described in Section 3.1, the Haenni accuracy specifications for these weights were ± 70 lb for the nose wheel weight and ± 210 lb for the main gear weights. The nominal value (from Table 6.1) was 290.3 inches. Using the maximum positive error on the nose wheel and the maximum negative error on the main gear wheels, the forward limit would be 289.2 inches. Reversing this process gives an aft limit of 291.3 inches. Similar calculations can be performed for all aircraft and scales but the concept is that the calculated centre of gravity is accurate to about ± 1 inch.

6.3 Aircraft Centre of Gravity Limits

When dealing with the weight and balance sheets of most large aircraft, the centre of gravity limits are

TABLE 6.1
CENTRE OF GRAVITY CALCULATIONS

AIRCRAFT	SCALES	MM (lb)	ML (lb)	MR (lb)	MT (lb)	XL+XR (in)	YL+YR (in)	XCG (in)	YCG (in)
CHALLENGER A	BENCHMARK *	2,850	13,075	13,065	28,990	266.0		289.4	
		2,840	13,070	13,050	28,960	266.0		289.5	
	HAENNI	2,205	13,307	13,190	28,702	314.4	62.8	290.3	-0.26
		2,079	13,329	13,175	28,583	314.4	62.8	291.5	-0.34
	INTERCOMP	2,150	12,450	12,250	26,850	314.4	62.8	289.2	-0.47
		2,150	12,500	12,400	26,850	314.4	62.8	289.2	0.23
	PAT	2,240	13,360	13,280	28,880	314.4	62.8	290.0	-0.17
		2,300	13,480	13,220	29,000	314.4	62.8	289.5	-0.56
CHEYENNE	HAENNI	1,228	3,792	3,761	8,781	127.5	112.5	109.7	-0.40
		1,223	3,836	3,704	8,768	127.5	112.5	109.6	-1.79
		1,228	3,836	3,682	8,746	127.5	112.5	109.6	-1.99
	INTERCOMP	1,200	3,650	3,450	8,300	127.5	112.5	109.1	-2.71
		1,250	3,650	3,550	8,450	127.5	112.5	108.6	-1.33
		1,250	3,650	3,500	8,400	127.5	112.5	108.5	-2.01
	PAT	1,280	3,860	3,780	8,920	127.5	112.5	109.2	-1.01
		1,240	3,850	3,760	8,880	127.5	112.5	109.7	-1.52
		1,240	3,940	3,780	8,960	127.5	112.5	109.9	-2.01
CONQUEST	HAENNI	1,030	3,512	3,389	7,930	149.0	84.0	129.7	-1.31
	INTERCOMP	950	3,700	2,950	7,600	149.0	84.0	130.4	-0.29
	PAT	1,020	3,580	3,400	8,000	149.0	84.0	130.0	-1.09
CHALLENGER B	HEANNI	2,740	13,052	12,860	29,452	314.4	62.8	285.1	-2.11
		2,718	13,052	12,926	29,496	314.4	62.8	285.4	-1.97
	INTERCOMP	3,000	12,750	11,850	27,600	314.4	62.8	280.2	-2.05
		3,000	12,600	11,650	27,250	314.4	62.8	279.8	-2.19
	PAT	2,740	13,790	13,060	29,560	314.4	62.8	285.3	-1.49
		2,740	13,780	13,100	29,620	314.4	62.8	285.3	-1.44
METROLINER	HEANNI	1,521	3,505	3,993	8,920	229.6	90.0	190.4	3.91
		1,528	3,490	3,865	8,882	229.6	90.0	190.1	3.80
	INTERCOMP	1,450	3,250	4,000	8,700	229.6	90.0	191.3	7.76
		-	-	-	-	229.6	90.0	-	-
	PAT	1,340	3,540	4,000	9,080	229.6	90.0	190.7	4.56
		1,540	3,540	4,000	9,080	229.6	90.0	190.7	4.56
HS125	HEANNI	1,823	7,884	8,318	18,025	252.5	55.0	227.0	1.33
		1,962	7,701	8,325	17,987	252.5	55.0	225.8	1.91
	INTERCOMP	1,850	7,400	8,350	17,600	252.5	55.0	226.0	2.97
		1,900	7,450	8,400	17,750	252.5	55.0	225.5	2.94
	PAT	1,980	7,940	8,360	18,280	252.5	55.0	225.2	1.26
		1,980	8,000	8,340	18,320	252.5	55.0	225.2	1.02

* Jacking points of benchmark scales not coincident with landing gear.

SOURCE: AVIATION PLANNING SERVICES ANALYSIS

presented in terms of mean aerodynamic chord (M.A.C.). On smaller aircraft, the reference is a datum point and linear dimensions fore and aft. These limits are often a function of aircraft certification and weight, becoming more restrictive as the weight increases. The following exercise can be performed on all aircraft. One example was done for this study.

Figure 6.4 is an extract from the Canadair Challenger's operating manual and shows the centre of gravity limits of that aircraft. Other pertinent data also extracted from the aircraft manual are:

- Nose wheel axis centreline at FS228.4 inches
- Main gear axis centreline at FS542.8 inches
- Beginning of M.A.C. at FS488.0 inches
- Length of M.A.C. 92.6 inches.

It should be noted that longitudinal locations on an aircraft are given with reference to some pre-defined datum. Other distances relative to this datum are given as Fuselage Station (FS) in inches. Therefore, given the FS distance of the nosewheel, the certified limits of the C of G in FS terms, and our computed C of G in relation to the nosewheel, it can be determined if the aircraft is loaded within limits.

In our test case for the Challenger A, an aircraft weight of 29,000 lb, the centre of gravity limits were 18% M.A.C. and 31.35% M.A.C. This translated to FS504.7 inches and FS517.0. With respect to the nose gear, these values[1] are 276.3 inches and 288.6 inches. By comparing these values with the APS calculated values, i.e., approximately 290 inches (from Table 6.1), it can be seen

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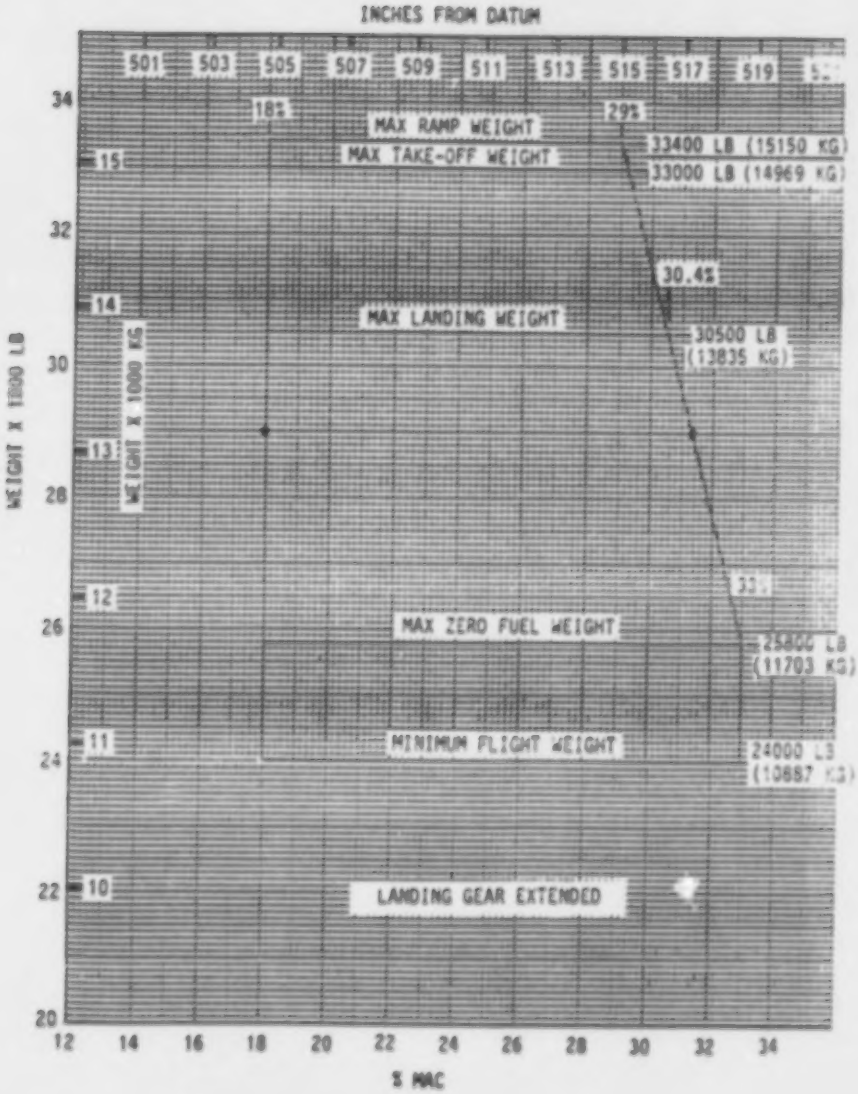
[1] Obtained by subtracting X_{cg} from FS of the nose gear.

FIGURE 6.4
CANADAIR CHALLENGER
WEIGHT AND BALANCE DOCUMENT

canadair challenger

OPERATING MANUAL



Centre of Gravity Limits
Figure 1

LIMITATIONS
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Source: Canadair Challenger Operating Manual

that the centre of gravity is outside the limiting range. This is not unexpected as the aircraft tested were not ready to fly, missing crew and other moment generating weights. The addition of a single pilot can shift the centre of gravity forward by as much as two inches.

The important aspect for actual enforcement is to have the published centre of gravity limits - whether they are in % M.A.C., or with respect to a physical point on, or in front of, the aircraft - converted to values with respect to the nose wheel. As shown, the calculations are neither difficult nor time consuming.

7. CONCLUDING REMARKS

The results of the binary analysis indicate that the most preferable scale for Transport Canada is that manufactured by Haenni. The PAT scale also received a relatively good score but fell short in some key areas, notably, pad weight, pad thickness, and ease of operation. These were judged to be the most important elements of the analysis. The Intercomp scales' main advantage was their computer but the pads themselves were lacking in several areas and did not meet their own accuracy rating during the testing.

The final decision on the acquisition depends not only on the technical aspects considered in this study but also on two other important factors. The first is cost, which was addressed earlier. The second is the legality and procedures for effecting a weighing exercise for enforcement purposes in the field.

The second issue is not unlike the police force issue of stopping motorists for routine checks or suspect checks. TC personnel at this time do not appear to be confident that, with any scale, a process could be developed whereby a loaded aircraft, ready for flight could be stopped, weighed and, if necessary, sustainable charges laid. It is the consultants belief that considerable public and administrative education would be needed to accept the concept of "spot weighings" similar to road "spot check", with a high probability of success. Further discussion of this issue has not been pursued as it is beyond the scope of the present mandate. However, this issue does need to be addressed further.

Finally. the conclusion is this report has lead to the second and third phases. These involve modelling of wind effects and float plane weighing system development. The scales to be used in these phases will be the Haenni scales. The reports

from these two phases will be produced as an independent document to follow this report.

APPENDIX A

SAMPLE RAW DATA

Included here are three sample data sheets from the actual field trials. The physical dimensions were included later as only one set of measurements were required per aircraft.

AVIATION PLANNING SERVICES LTD.
PORTABLE WEIGH SCALES

DATA RECORDING SHEET

PROJECT: 971-1

DATE: 22/Feb

TIME STARTED: 248

TIME ENDED: _____

AIRCRAFT: Cheyenne

BENCHMARK WEIGHT: /

TRIAL NUMBER: #7

SCALES USED: PAT 3

WEIGHTS:		
	FRONT SCALE:	1240
	LEFT SCALE:	3780
	RIGHT SCALE:	3940
	TOTAL:	8960

Wheel Thickness:
Nose 4 3/8
Main 5"

WHEEL ~~BASE~~ TRACK (INTERIOR-INTERIOR) 220"

NOSE GEAR - MAIN GEAR DIRECT

LEFT: 168"

RIGHT: 168"

NOSE GEAR - MAIN GEAR AXIS 128 3/4"

WEIGHED BY (INITIALS): [illegible] ; [illegible]

COMMENTS:

AVIATION PLANNING SERVICES LTD.
PORTABLE WEIGH SCALES

DATA RECORDING SHEET

PROJECT: 971-1

DATE: 22/Feb

TIME STARTED: 1 35

TIME ENDED: _____

AIRCRAFT: challenger

BENCHMARK WEIGHT: _____

TRIAL NUMBER: 4

SCALES USED: INTERCOMP 2

WEIGHTS:		
	FRONT SCALE:	2150
	LEFT SCALE:	12450
	RIGHT SCALE:	12250
	TOTAL:	26850

Wheel Thickness
Nose 16½"
Main 21"

WHEEL ~~BASE~~ TRACK: 104½"

NOSE GEAR - MAIN GEAR DIRECT

LEFT: 317±"

RIGHT: 317±"

NOSE GEAR - MAIN GEAR AXIS: 314½"

WEIGHED BY (INITIALS): GK ; JB

COMMENTS:

AVIATION PLANNING SERVICES LTD.
PORTABLE WEIGH SCALES

DATA RECORDING SHEET

PROJECT: 971-1

DATE: 23 Feb

TIME STARTED: 1'15

TIME ENDED: _____

AIRCRAFT: Merlin

BENCHMARK WEIGHT: /

TRIAL NUMBER: 1

SCALES USED: HAENNI

WEIGHTS:

FRONT SCALE:	690
LEFT SCALE:	1590
RIGHT SCALE:	1766
TOTAL:	4046

kgs

WHEEL ~~BASE~~ TRACK (INT - INT) 164¼"

NOSE GEAR - MAIN GEAR DIRECT

LEFT: 244"

RIGHT: 244"

NOSE GEAR - MAIN GEAR AXIS 230½"

WEIGHED BY (INITIALS): AB ; AL

COMMENTS:

APPENDIX B

BINARY DECISION MODEL

The application of the model involves the following steps:

Step 1 **Identify the Important "Decision Criteria" or "Decision Variables"**

This involves simply enumerating the factors, both quantitative and qualitative, which should be considered in selecting a weigh scale system from the perspective of a decision maker faced with a major capital expenditure. An effort is made to keep this list as short as possible without excluding any important variables, and to minimize the "double-counting" or duplication of variables. In other words, the criteria selected must be mutually exclusive and collectively exhaustive.

Step 2 **Weighting the Decision Criteria**

Having identified the major decision criteria, it is necessary to attach relative weights to each criterion, as they are not all equally important to the selection process. APS' binary decision analysis technique was used to establish the relative weights of the decision criteria.

The technique requires examining every possible pair of criteria, deciding which of the two criteria is the most important, and then assigning a 1 to the most important and 0 to the less important criterion. After every pair is evaluated the number of 1's received by each criterion is calculated to produce a "raw" total score. The highest scoring criterion is the most important. A

simple mathematical transformation[1] is then performed to convert the raw scores into percentage weights or scores. A relative ranking can be assigned based on the percentage scores.

Step 3 **Evaluating Weigh Scale System Using the Decision Criteria**

This step involves an assessment of each weigh scale model, to establish a ranking on the basis of ability to satisfy the criterion being considered. Again a binary decision analysis process is used. It involves examining the concepts in pairs, deciding which of the two concepts best meets the criterion being considered, and then assigning a 1 to the preferred type, and 0 to the less desirable type. After every pair of systems has been systematically analyzed in this manner, a total is computed. The weigh scale systems with the highest score on a particular criterion is considered the best in fulfilling the demands of that criterion.

Step 4 **Applying the Criteria Weights to the Evaluation Scores to Produce a Final Weighted Score for each System**

In the previous step each system was evaluated on the basis of its ability to satisfy the criterion being considered without any regard for the relative importance or weight of the criterion. In the unweighted form, each criterion has equal value. For example, pad thickness cost is assumed to be just as important as reliability. Therefore, it is now necessary to weigh each system's score by the applicable criterion weight, so that the relative importance of each criterion can be

---

1 Unity is first added to every raw score to ensure no zero scores are present and then each score is converted into a percentage figure.

incorporated. This is accomplished by multiplying the relative weights assigned to each of the criteria, by the scores assigned to weigh scales system for each criterion. This process produces a weighted score of each concept for each criterion considered. The total weighted score for each system is calculated by adding up the criteria weighted scores associated with a particular aircraft, and normalizing to unity.

It should be noted that the use of the binary decision analysis technique in this application requires such a large number of individual decisions to be made that any subjective biasing of the results by the analysis is highly improbable.

SAMPLE COMPUTATION OF BINARY ANALYSIS

Suppose there are three criteria (A, B, C) and two alternatives (X, Y)

1. **Weighting of Criteria**

Criterion	Raw Score	Total Score	Transformed Score	Criterion Weight
A	1 1	2	3	50%
B	0 0	0	1	17%
C	0 1	1	2	33%
		3	6	100%

Notes:
- "A" is more important than "B"
- "A" is more important than "C"
- "C" is more important than "B"
- Total Score is sum of Raw Scores
- Transformed Score is Total Score plus 1
- Weight is equal to $\frac{\text{Transformed Score}}{\text{Total Transformed Score}}$

2. **Evaluation of Alternatives Using Criteria**

a) **For Criterion "A"**

Alternative	Raw Score	Total Score	Transformed Score	Criterion Weight
X	1	1	2	67%
Y	0	0	1	33%
		1	3	100%

Note: For Criterion "A", "X" is more important than "Y"

b) **For Criterion "B"**

Alternative	Raw Score	Total Score	Transformed Score	Criterion Weight
X	0	0	1	33%
Y	1	1	2	67%
		1	3	100%

c) **For Criterion "C"**

Alternative	Raw Score	Total Score	Transformed Score	Criterion Weight
X	1	1	2	67%
Y	0	0	1	33%
		1	3	100%

3. **Final Scores and Ranking**

Alternatives	Score per Criterion A	B	C	Total Score
X	33.5	5.6	22.1	61.2
Y	16.5	11.4	10.9	38.8
				100.0

Note: Cell "XA" = Criteria Weight "A" multiplied by Alternative "X" for Criterion "A" divided by 100 = 50 multiplied by 67 divided by 100

Therefore, Cell "XA" = 33.5

DEMONSTRATION AND PERFORMANCE EVALUATION OF SELECTED PORTABLE WEIGH SCALES FOR DETECTION OF OVERLOADED AIRCRAFT

PART 3

INCLUDES

PHASE II - WIND EFFECTS COMPENSATION

PHASE III - OVERLOADED SEAPLANE DETECTION

PREPARED FOR

TRANSPORTATION DEVELOPMENT CENTRE
RESEARCH AND DEVELOPMENT DIRECTORATE
POLICY AND COORDINATION GROUP
TRANSPORT CANADA

BY

AVIATION PLANNING SERVICES LTD.

AUGUST, 1990

The contents of this report reflect the analysis and conclusions of Aviation Planning Services Limited and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

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EXECUTIVE SUMMARY

This component of the report describes Part 2 of the project "Demonstration and Performance Evaluation of Selected Portable Weight Scales for Detection of Overloaded Aircraft", which includes the final two phases of a three-phase project concerned with the practical measurement of aircraft weights in the field. The objectives of these final phases were:

1) to quantify the effect of wind on the measured weight of an aircraft;

2) to develop procedures by which the gross weights of float planes or seaplanes could be determined.

The Transportation Development Centre (TDC) contracted this work on behalf of Enforcement and Legislation of Transport Canada's Aviation Group (TCAG). The study was performed by and in response to recommendations made by Aviation Planning Services Ltd. (APS) in a February 1989 report: "Portable Weigh Scales for Detection of Overloaded Aircraft". A Phase I report titled "Demonstration and Performance Evaluation of Selected Portable Weight Scales for Detection of Overloaded Aircraft, Part 1", evaluating three portable weigh scale systems was submitted in May 1990. It concluded with a recommendation of one type of portable weigh scale for use by TCAG.

The general methodology for Phases II and III involved:

- using an initial hypothesis to conceptualize and develop a mathematical model of the situation;

- conducting field trials by weighing aircraft in a real wind condition or in water as appropriate (test sites were Montreal International Airport (Dorval) for Phase II and the Marina Venise (Laval) for Phase III);

- analyzing both the mathematical models and the recorded data to ascertain the degree of accuracy of the models; and establishing operating procedures.

In Phase II (Wind Compensation), it was concluded that an aircraft weighed under wind conditions and found to be overloaded was actually overloaded, within the accuracy of the scales, subject to the following conditions:

- the aircraft be weighed in a relatively steady wind of magnitude 10 knots or less; and

- the angle between the wind direction and the aircraft longitudinal centre line be limited to a range between -90° to +90°, where 0° is measured directly towards the nose of the aircraft.

A further conclusion was that the effect of the wind in these instances would be such that marginally overloaded aircraft would not be conclusively determined to be overloaded.

In Phase III (Overloaded Seaplane Detection) it was established that it is possible for an enforcement officer to measure the gross weight of a float plane simply by measuring the waterline at two points on one side of each float. The officer must have all the specific float data and the use of a computer. The limiting condition with the method is that the water must be relatively calm to allow the officer to make a reasonably precise measurement. Here, the margin of error ranged from 0% - 5%.

In conclusion, for wind compensation, it was recommended that TCAG conduct actual weighings under conditions similar to those tested by APS and with aircraft used during this study. The results would be invaluable in establishing the validity of the procedures . For the seaplane case, it was recommended that a data base of the models of all aircraft in Canadian service be developed and

provided to TCAG, along with procedures for its use. Finally, a caution was noted that preceding the "spot checks" implementation, an educational program be undertaken by TC to alert the public of the need for the checks.

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GLOSSARY AND NOTATION

A_l	lift area
A_d	drag area
APS	Aviation Planning Services Ltd.
B_i	individual immersed element buoyancy
C_L	lift coefficient
C_D	drag coefficient
CG	centre of gravity
CP_D	centre of pressure for drag
CP_L	centre of pressure for lift
d1	half distance between main gear
d2	distance from rear gear to front gear
dD	axial dist - front gear to drag centre
dDT	transverse dist - c/l to centre drag
dL	axial dist - front gear to lift centre
dLT	transverse dist - c/l to centre lift
dW	axial dist - front gear to c.g.
dWT	transverse distance - centreline to c.g.
F_{Drag}	drag force
F_{Lift}	lift force
F_{nose}	force on nose gear
F_{left}	force on left gear
F_{right}	force on right gear
F_{Total}	load total
g	gravitational acceleration
hD	elevation of centre of drag
NAE	National Aeronautical Establishment
Rey	Reynolds number
Rho	density of water
TCAG	Transport Canada Aviation Group
TDC	Transportation Development Centre
V_i	individual element submerged volume
V1	air speed at left wing tip

GLOSSARY AND NOTATION - Continued

V_2	air speed at right wing tip
V	root mean square air speed
W	weight of aircraft
μ	friction factor
σ	slew angle

1. GENERAL INTRODUCTION

At the request of the Transportation Development Centre (TDC) of Transport Canada, Aviation Planning Services Ltd. (APS) undertook the evaluation of selected portable weigh scales which could be used to detect overloaded aircraft. This evaluation was detailed in the Phase I report titled, "Demonstration and Performance Evaluation of Selected Portable Weight Scales for Detection of Overloaded Aircraft, Part I".

The evaluation of the scales was but one aspect of the overall study. This report deals with two other areas of study: Wind Effects Compensation (Phase II); and Overloaded Seaplane Detection (Phase III). Each phase is presented separately.

In Phase I of the study, it was found that the scales manufactured by Haenni, Switzerland, were the most appropriate for Transport Canada's purposes. Therefore these scales were used in Phase II and Phase III testing.

PHASE II - WIND EFFECTS COMPENSATION

2. INTRODUCTION

The area of wind compensation was studied with one essential goal: to quantify the effect of wind on the measured weight of an aircraft. This is important for enforcement purposes as it must be known whether wind effects can cause an aircraft which is not overloaded to appear overloaded or vice-versa.

This section of the report documents the methodology and analysis used to study this phenomenon.

2.1 Problem Definition

We have defined the problem as estimating the effect of wind on aircraft weight measurement. In this study, wind velocity and direction with respect to the aircraft centre line are assumed to be fundamental parameters for the development of a suitable technique. The lift and drag coefficients C_L and C_D are calculated and the effect on the vertical force at each landing gear assembly can be estimated.

2.2 Aircraft Under Study

In view of the "proof of concept" nature of this study, the analysis was done on only a single aircraft type. If the method proved to be successful then similar studies could be applied to other aircraft types with the techniques proved here. The original focus of the study was on small, light aircraft, such as a CESSNA 206. It was felt that this light aircraft would be both accessible to the consultants and easily manoeuvrable during field trials. Wind tunnel tests were conducted using a commercial, $1/48^{th}$ scale model of a CESSNA 150 and a $1/50^{th}$ scale model of a SOCATA MS 235, as a scale model of the CESSNA 206 was unavailable.

2.3 Methodology

The methodology consisted of the following steps:

2.3.1 Initial Hypothesis

This involved establishing a general hypothesis which APS could use as a basis in formulating an analysis technique.

2.3.2 Literature Survey and Information Search

The survey included an on-line computer search as well as discussions with an aircraft manufacturer and the National Aeronautical Establishment (NAE) in Ottawa.

2.3.3 Computational Model

The computational model required the definition of the relevant parameters and the derivation of appropriate analytical equations.

2.3.4 Field Trials

The field trial aspect of the project involved recording actual aircraft weights under various wind speeds and directions.

2.3.5 Wind Tunnel Tests

The wind tunnel tests were used to supply lift and drag values with controlled wind speeds and directions.

2.3.6 Modelling and Analysis

The analysis considered all aspects of the project. The field trials, wind tunnel tests and computational modelling were all examined.

3. ANALYSIS AND EXPERIMENTATION

3.1 Initial Hypothesis

From observations of aircraft on the ground under windswept conditions, it is known that the wind can have an effect on the load carried by the landing gear. We also know that aircraft can be up-turned, flipped and lifted by the wind during extreme conditions. However, how the effect varies with the velocity and direction of the wind is not clear.

We hypothesized that the effect of wind on landing gear loading is related to the velocity and direction of the wind and to the lift and drag profiles of the aircraft. We also hypothesized that while the drag is experienced over the entire aircraft, the lift is dominated by the wings. No fuel slosh or unsteady effects were considered.

3.2 Literature Survey and Information Search

The purpose of the literature review was to establish whether any research, directly or indirectly related to wind effects compensation, had been carried out in the past. If such research was found, the next task was the procurement and analysis of the results, to avoid wasting time on the repetition of work already completed.

The search was undertaken in three forms[1]:

1) A computerized search among technical paper data

---

[1] It is known that one manufacturer of portable weigh scales is conducting research on wind effects. However, neither the manufacturer's results nor the study were available for inclusion here.

bases;

2) Contact with a glider manufacturer;

3) A discussion with scientists at the National Aeronautical Establishment (NAE) in Ottawa.

Because the number of reference papers in the field of aerodynamics is extremely large, the search was narrowed down to those papers of specific interest, through an on-line computer search. The computer was used to access three technical paper data bases; the "Engineering Index", "NTIS", and the "Aerospace Database".

The result of the on-line literature search was a NASA Contractor Report 2971, entitled "Static Aerodynamic Characteristics of a Typical Single-Engine Low-Wing General Aviation Design for an Angle-of-Attack Range of -8° to 90°," by Bihrle, Barnhart and Pantason. The report covers both angle of attack and sideslip in the range -10° to -30°, for a 1/7th scale, "typical low-wing, single-engine, light general aviation airplane" at a Mach number of 0.2 and Reynolds numbers of $2.88(x10^5)$ and $34.5(x10^5)$. The report presented raw data in graphical form. The data showed that the side force coefficient varies linearly from about 0.1 to -0.3, over angles of attack from -8° to 90°. Furthermore, the "rolling moment" coefficient varied from 0.04 to -0.10. Thus there is a measured strong dependence of aircraft load on sideslip velocity.

In addition, Switzer Aviation of Elmira, New York, was contacted, and promised to send an information package. However, it has failed to do so for reasons APS could not determine within the time constraints of the study. This manufacturer was contacted because, dealing with gliders,

they may have some relevant, very low speed, testing procedures or data.

APS planned to measure the load on each landing gear of a light, high-wing aircraft at a non-zero wind velocity. Consequently, NAE scientists were asked whether they had undertaken:

(a) similar full-scale measurements;

(b) related wind-tunnel trials; and/or

(c) analyses.

The reply was negative. Thus, essentially NAE could not provide any input to the study.

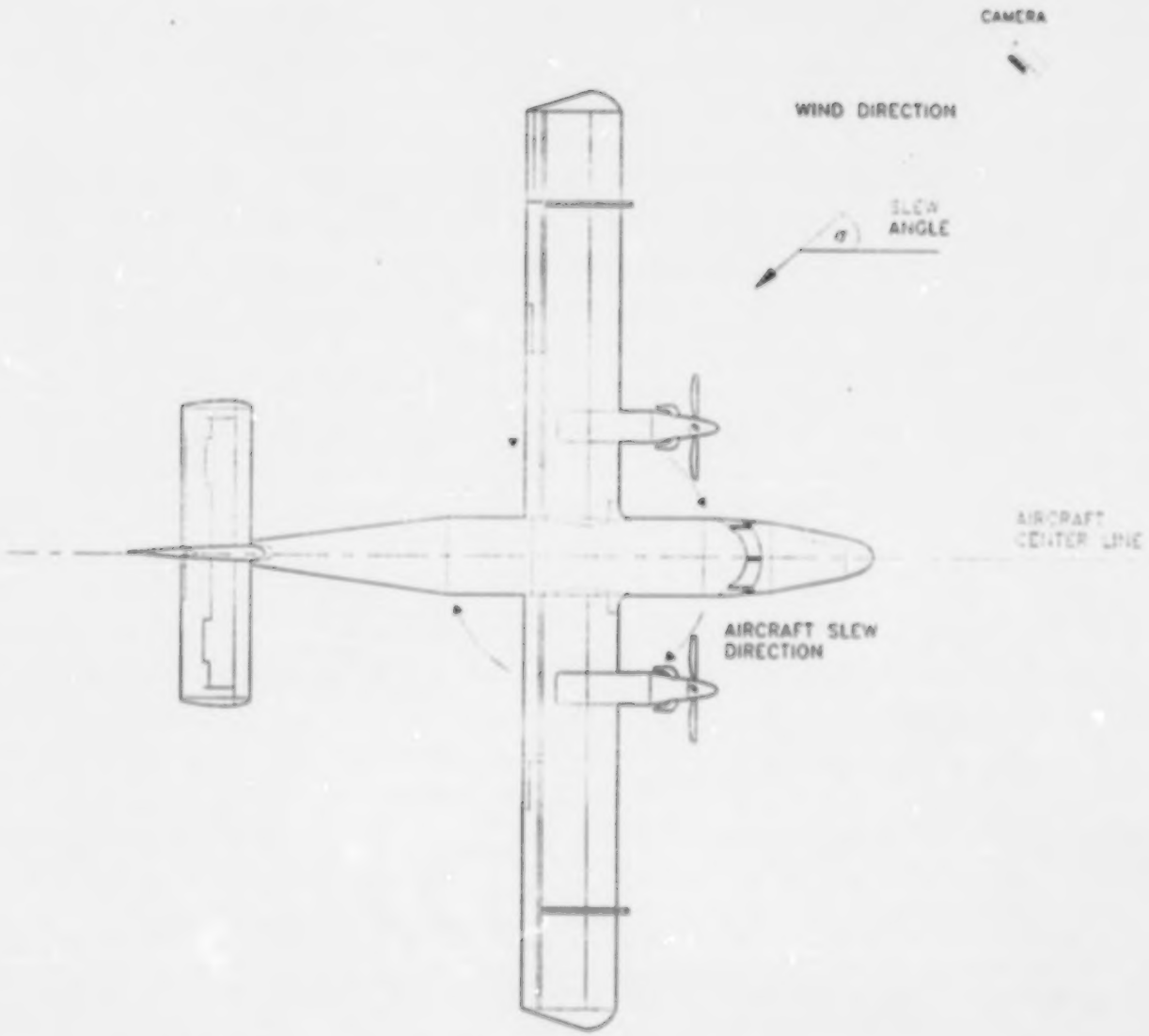
3.3 Computational Model

A computational model from the Phase I report was enhanced to include the effect of wind loading on the weigh scale measurements.

In the analysis, wind over the wing is presumed to produce lift, while it also produces drag over the entire aircraft. The direction of the wind relative to the longitudinal centre line of the aircraft defines the "slew" angle (σ). The slew angle is described in Figure 3.1. Both lift and drag effects are distributed to the three portable weigh scales used to measure the overall weight of aircraft.

Each weigh pad is loaded by a portion of the aircraft weight. In addition, the effects of lift and drag are shared by each of the three pads. For an aircraft not subject to wind loading, the sum of the measurements provides the aircraft weight, and, as indicated in the

FIGURE 3.1
DESCRIPTION OF SLEW ANGLE



Source: APS Illustration

Phase I Report, can be used to determine the aircraft's centre of gravity.

One type of drag effect (form drag), which is considered significant here, acts over surfaces that are approximately perpendicular to the air flow. Therefore, the drag acts on the projected area of the aircraft in the wind flow direction. The drag force can be placed at the geometric centre of that projected area. On the other hand, the lift effect acts along surfaces that are in the flow direction. Because the fuselage of an aircraft is approximately symmetrical about the longitudinal axis and the surface areas of the tail surfaces are small compared to the area of the wing, lift is presumed to occur on the wing only. As a check in the calculation, we monitored the axial location of the centre of lift and the closeness of the centre of lift to the centre line of the aircraft.

It has been assumed that the winds are parallel to the ground. In addition, we did not separate out ground effects. Also, because the weigh scales cannot measure the frictional, transverse loading at the landing gears, it has been assumed that the transverse load at each gear is proportional to the measured weight and that the proportionality constant is the same for each.

The projected area for drag was obtained using digital images of photographs of aircraft at various slew angles. Examples of this are provided in subsection 3.3.2.

3.3.1 Landing Gear Load Analysis

Figure 3.2 shows the geometry for taking moments necessary for the static balancing of the aircraft. First the total vertical load on all cells is described by the expression:

$$F_{nose} + F_{right} + F_{left} + F_{Lift} - W = 0$$

That is, the sum of cell loads, F_i, and the lift, F_{Lift}, balance the aircraft weight.

Next, the load on each cell has three components, namely portions of W_i the aircraft load, F_{Li} the lift and F_{Di} the drag. Thus, the load at each scale is

$$L_i = W_i + F_{Li} + F_{Di}$$

The aircraft weight, W, is assumed to act at the centre of gravity, CG, the drag force, F_{Drag}, acts at the centre of pressure, CP_D, for drag, and the lift force, F_{Lift}, at the centre of pressure for lift, CP_L. The centre of gravity, CG, is furnished by measurements in quiescent (zero wind) environments.

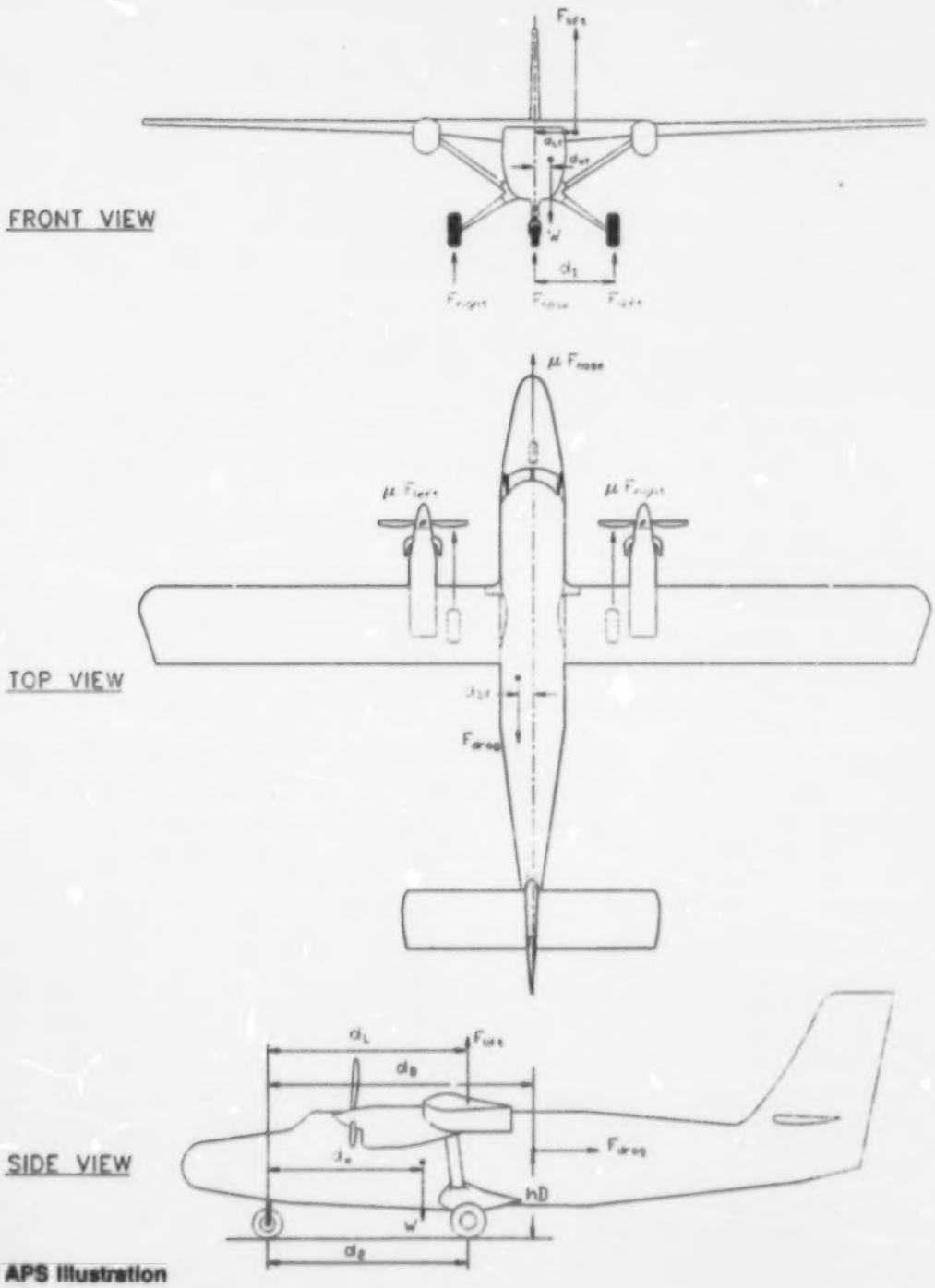
Nomenclature is provided in Table 3.1.

As presented earlier, the overall vertical force balance is given by

$$F_{nose} + F_{right} + F_{left} + F_{Lift} - W = 0$$

where F_{nose}, F_{right}, and F_{left} are the loads measured by weigh scale pads at each landing

FIGURE 3.2
COMPUTATIONAL MODEL GEOMETRY



Source: APS Illustration

TABLE 3.1

COMPUTATIONAL MODEL NOMENCLATURE

A_L	lift area
A_D	drag area
C_L	lift coefficient
C_D	drag coefficient
CG	centre of gravity
CP_D	centre of pressure for drag
CP_L	centre of pressure for lift
d1	half distance between main gear
d2	distance from rear gear to front gear
dD	axial dist - front gear to drag centre
dDT	transverse dist - c/l to centre drag
dL	axial dist - front gear to lift centre
dLT	transverse dist - c/l to centre lift
dW	axial dist - front gear to c.g.
dWT	transverse distance - centreline to c.g.
F_{Drag}	drag force
F_{Lift}	lift force
F_{nose}	force on nose gear
F_{left}	force on left gear
F_{right}	force on right gear
F_{Total}	load total
g	gravitational acceleration
hD	elevation of centre of drag
V1	air speed at left wing tip
V2	air speed at right wing tip
V	root mean square air speed
W	weight of aircraft
μ	friction factor
σ	slew angle

Source: APS Analysis

gear unit. The drag force, F_{Drag}, is presumed balanced by transverse friction between each landing gear and its weigh scale pad. The friction coefficient is presumed the same for all three gears. Thus,

$$(F_{nose} + F_{right} + F_{left}) \mu - F_{Drag} = 0$$

To obtain lift and drag due to wind effects we assume those forces have the form

$$F_{Lift} = C_L(Rey,\sigma)\ A_{proj.lift}(A_{full\text{-}plan},\sigma)\ V^2/2g$$

and

$$F_{Drag} = C_D(Rey,\sigma)\ A_{proj.drag}(A_{full\text{-}trans},\sigma)\ V^2/2g$$

where Rey is the Reynolds number, defined as the ratio of inertial to viscous forces. The lift area $A_{proj.lift}(A_{full\text{-}plan},\sigma)$ is a function of the area of the aircraft in a plan view and the slew angle, while the drag area $A_{proj.drag}(A_{full\text{-}longit},\sigma)$ is a function of the slew angle and the projected area in a longitudinal (side) view. Thus, F_{Lift} and F_{Drag} are functions of wind velocity, the angle between the airplane centre line and the wind direction, and lift and drag coefficients, C_L and C_D.

For convenience, these relations are reduced to

$$F_L = C_L A_{fl} V^2/2g$$

and

$$F_D = C_D A_{fd} V^2/2g$$

The velocity in the lift and drag force calculations is estimated as a root-mean-square combination of wind speeds measured at the left and right wing tips. These are measured as V_{right} and V_{left}. Although differences may produce a turning torque and an effect at the weigh scale pads, these effects are neglected.

The equations involve sets of moments.

The first set involves moments taken normal to the aircraft centre line:

(a1) around nose gear

$$F_{Drag}*hD - F_{right}*d2 - F_{left}*d2 - F_{Lift}*dL + W*dW = 0$$

(b1) around line through left and right landing gears

$$F_{nose}*d2 - W*(d2-dW) + F_{Lift}*(d2-dL) + F_{Drag}*hD = 0$$

(c1) around line through centre of drag, normal to aircraft centre line

$$F_{nose}*dD - W*(dD-dW) + F_{Lift}*(dD-dL) + (F_{right} - F_{left})*(dD-d2) + \mu*(F_{nose} + F_{left} + F_{right})*hD = 0$$

The second set involves moments taken parallel to the aircraft centre line:

(a2) around line through left landing gear

$$F_{nose}*d1 - W*(d1-dWT) + 2*F_{right}*d1 + F_{Lift}*(d1-dLT) = 0$$

(b2) around line through nose gear

$$F_{left}*d1 - W*dWT - F_{right}*d1 - F_{Lift}*dLT = 0$$

(c2) around line through right landing gear

$$2*F_{left}*d1 + F_{nose}*d1 - W*(d1+dWT) + F_{Lift}*(dLT+d1) = 0$$

The third set considers moments about vertical axes:

(a3) through nose gear

$$\mu*F_{left}*d1 - dDT*F_{Drag} - \mu*F_{right}*d1 = 0$$

(b3) through left gear

$$\mu*F_{nose}*d1 + 2*\mu*F_{right}*d1 - F_{Drag}*(d1-dDT) = 0$$

(c3) through right gear

$$2*\mu*F_{left}*d1 + \mu*F_{nose}*d1 - F_{Drag}*(d1+dDT) = 0$$

3.3.2 Projected Areas

To create a general formulation for use on a variety of aircraft we separate the effects of area and lift and drag coefficients.

Projected areas of the aircraft in the wind direction are found using digital images of aircraft photographs. The aircraft in each photo is clipped, darkened and digitized to form a high contrast image. The computer pixels that comprise the image are counted to obtain a representation of projected area. Length and height are calibrated from aircraft specifications. This technique neglects parallax and perspective, but provides adequate results for the analysis.

Plate 3.1 shows a photograph of a CESSNA 206 viewed at approximately 30° to the aircraft longitudinal axis. The aircraft image is formed as a shadow. The shadow is calibrated using known aircraft dimensions and the projected area is determined. In this case, the projected area is about 5.60 m^2 and the centre of the area is about 1.2 m above the ground.

Resulting areas for the 206 are given in Table 3.2. When viewed from the front, i.e., with a slew angle of 0°, the area of the aircraft appears to be 6.43 m^2 and the centre of area is 1.7 m above the ground. As another example, when viewed at 90°, the area is 7.27 m^2 and its geometric centre is 1.1 m above the ground. It should be noted that the photographs from which these values originated were taken from estimated slew angles and small inaccuracies may have resulted.

PLATE 3.1
CESSNA 206 AREA PROJECTION

Source: APS Photograph

TABLE 3.2
PROJECTED AREAS OF CESSNA 206

VIEWING ANGLE (Degrees)	PROJECTED AREA (m^2)	HEIGHT OF CENTRE OF AREA (m)
0	6.43	1.7
30	5.60	1.2
60	7.73	1.1
90	7.27	1.1
120	7.78	1.1
150	7.27	1.1
180	4.63	1.2

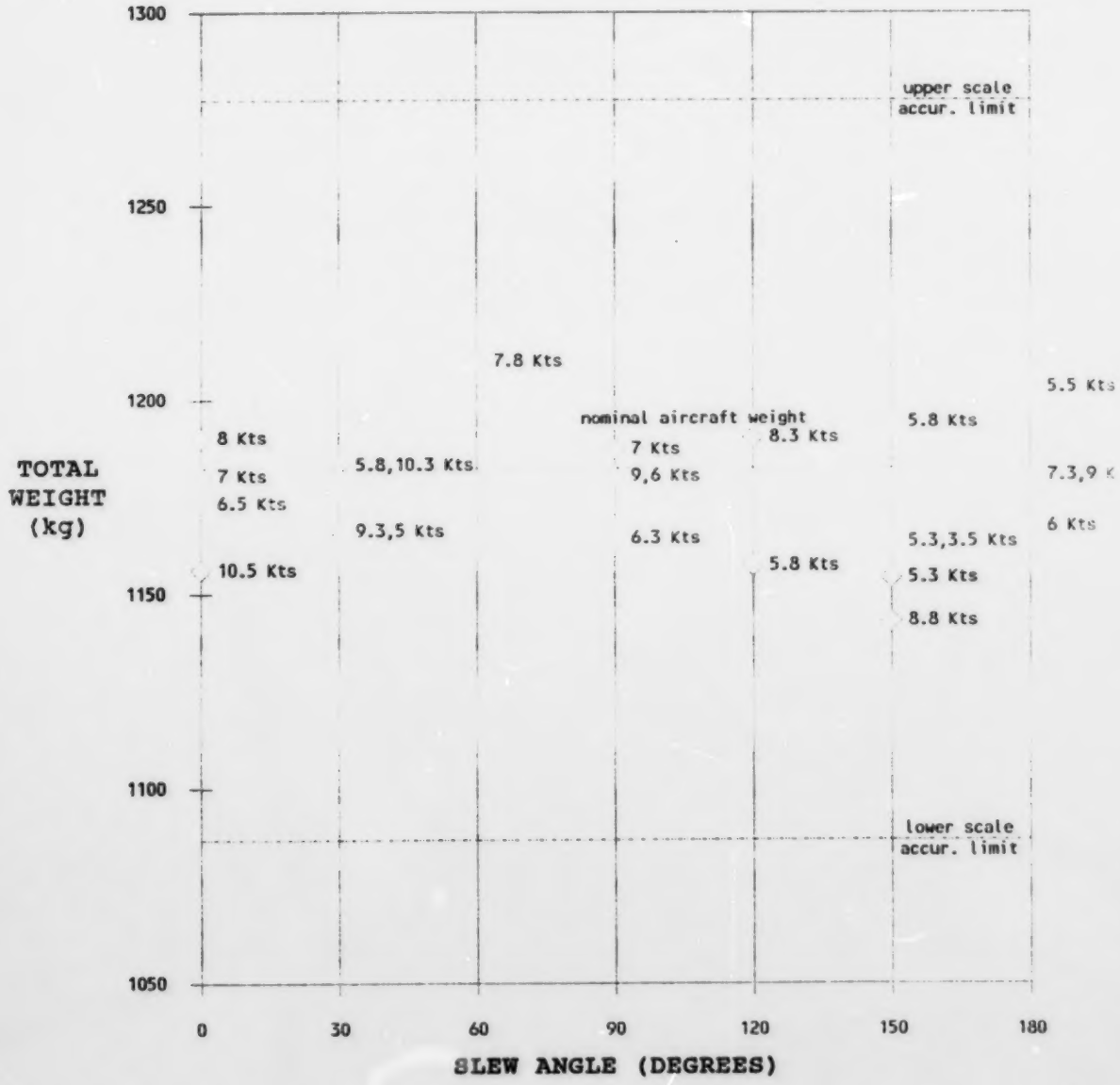
3.4 Field Trials

Field trials were conducted over two days outside the Transport Canada hangar at Dorval Airport.

The actual testing involved recording aircraft weights at various wind speeds and directions. The test aircraft were rotated so that the angle between the wind vector and the fuselage centre line (the slew angle) ranged from 0° to 180°. At the conclusion of the wind testing, the aircraft were moved indoors and benchmark, zero wind, weights were recorded.

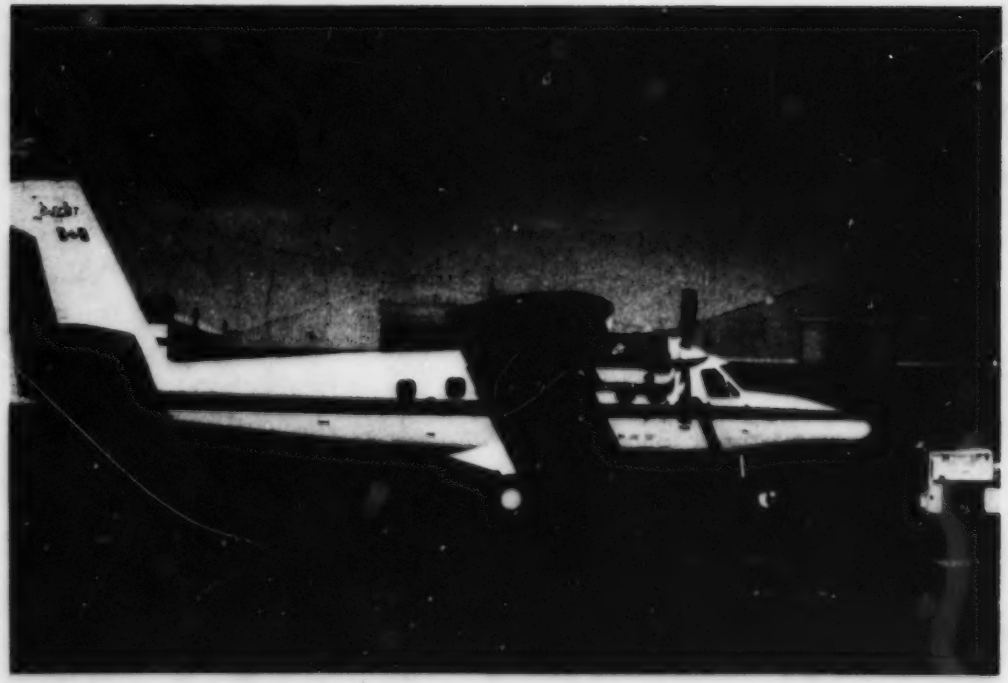
The winds on day one had magnitudes of 5 to 10 knots with variable directions. The aircraft tested was a CESSNA 206 (Stationair 6). Results from day one are plotted in Figure 3.3, which shows the measured weight as a function of slew angle at various wind speeds. The upper and lower accuracy limits are also shown on the diagram.

FIGURE 3.3
TOTAL RECORDED WEIGHT VERSUS SLEW ANGLE (WITH WIND SPEED) CESSNA 206



Source: APS Analysis

PLATE 3.2
TWIN OTTER



Source: APS Photograph

It should be noted that there does not appear to be any discernable pattern in the measurements. This may be due to:

1) Proportionately low aircraft weight for weigh pad capacity, i.e., the aircraft having a total weight of less than 1,400 kg allows for a margin of accuracy of ± 32 kg per pad. The potential error is significantly larger than any recorded wind effects and may overshadow any such effects.

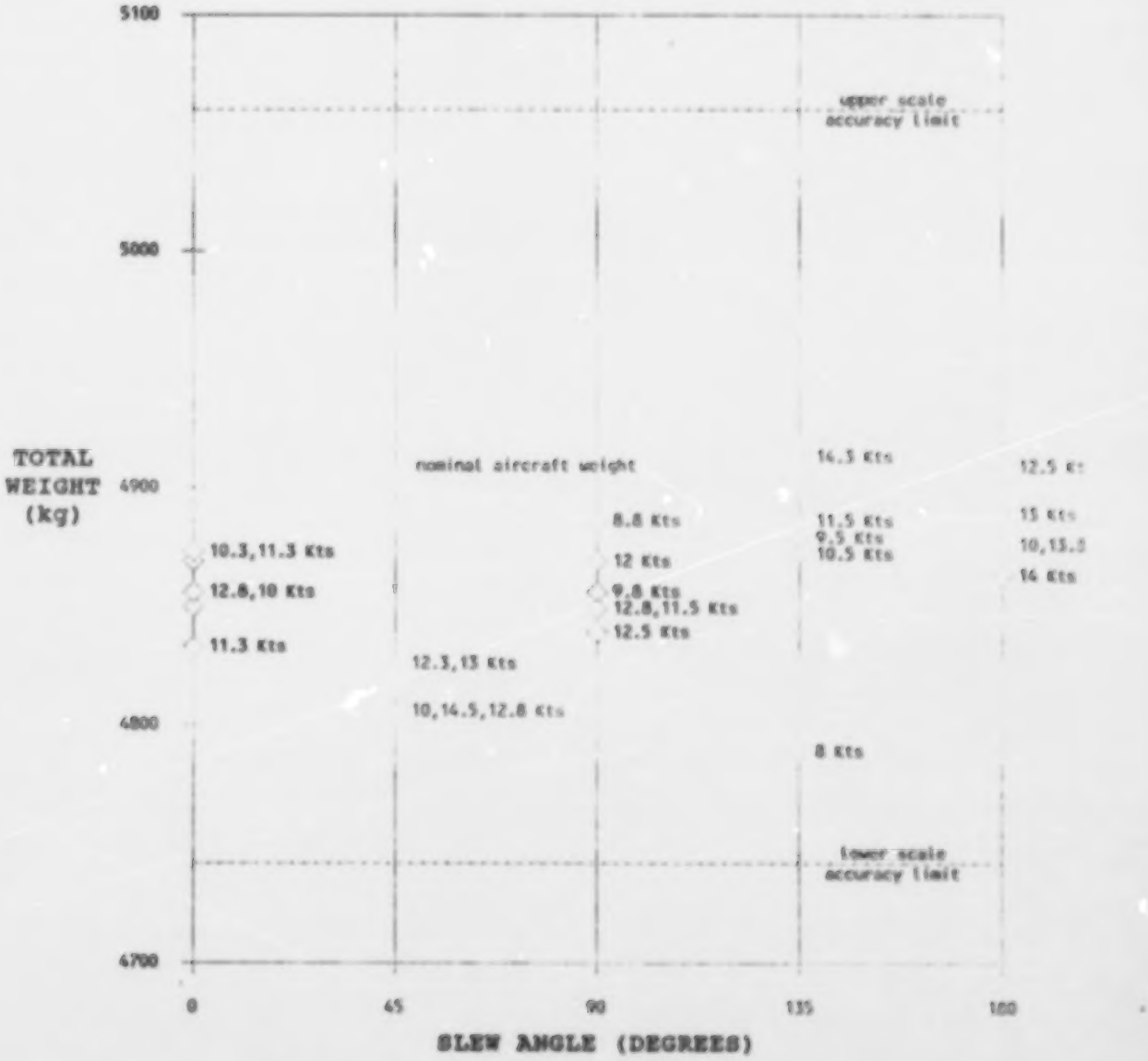
2) The wind itself being unsteady, involving slight gusts. Readings taken at one wing tip were often different from those taken at the opposite wing tip by as much as a factor of two.

Despite the lack of an apparent pattern, it should be noted that the measured weight was always well within the accuracy bounds of the scales.

It was decided, given the nature of the first day's results, to conduct an additional day of field trials. The second day's tests were performed on a Transport Canada Twin Otter. The Twin Otter used is shown in Plate 3.2. With the Twin Otter's high lift wings, it was expected that more consistent test results could be obtained.

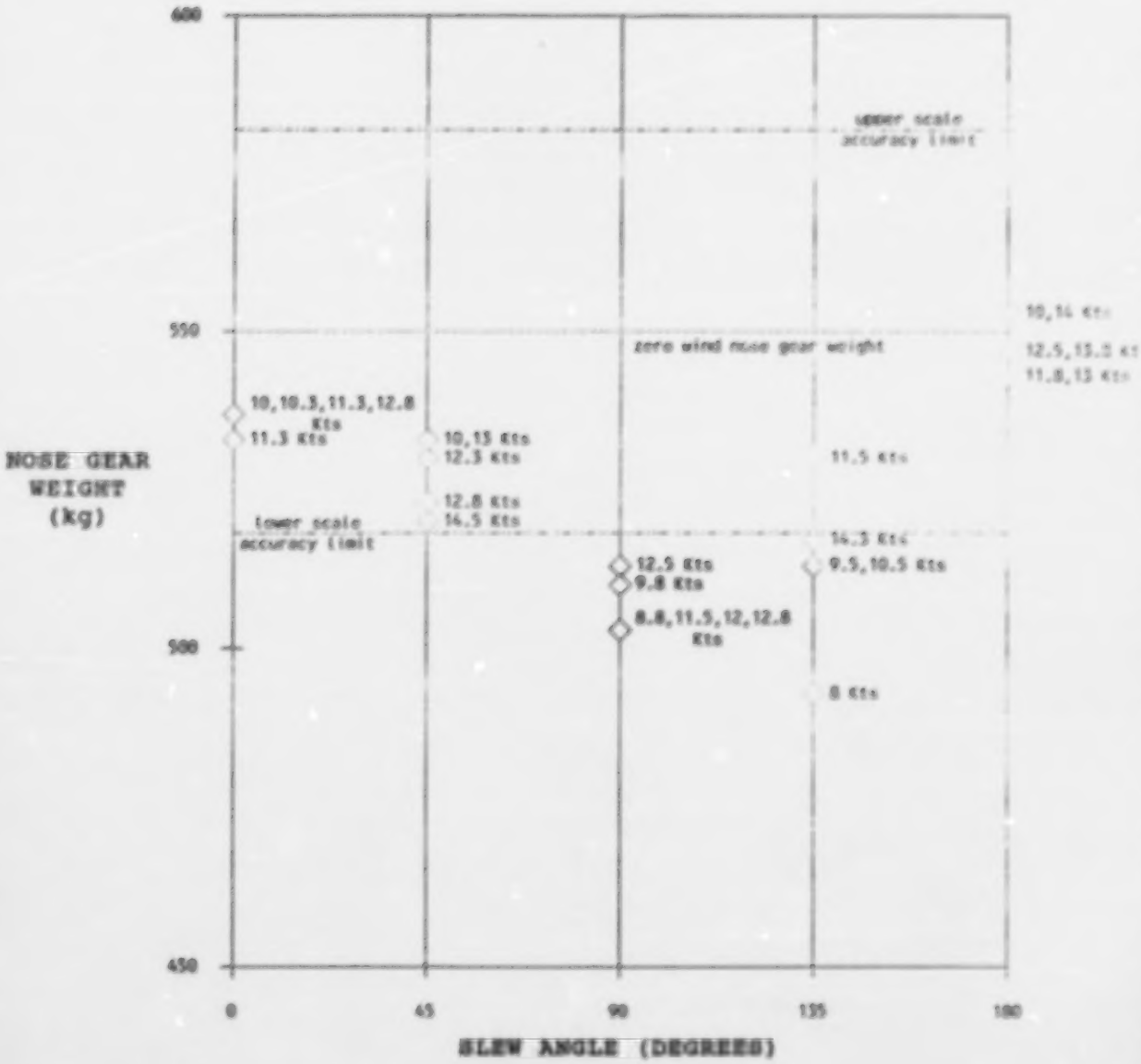
The wind on day two had a constant heading and had magnitudes which ranged from 10 to 15 knots. The results have been plotted in Figures 3.4 to 3.7 which show the total recorded weights and individual component weights on each landing gear unit. As can be seen in Figures 3.4 through 3.7, there were some very discernible patterns.

FIGURE 3.4
TOTAL RECORDED WEIGHT VERSUS SLEW ANGLE (WITH WIND SPEED) - TWIN OTTER



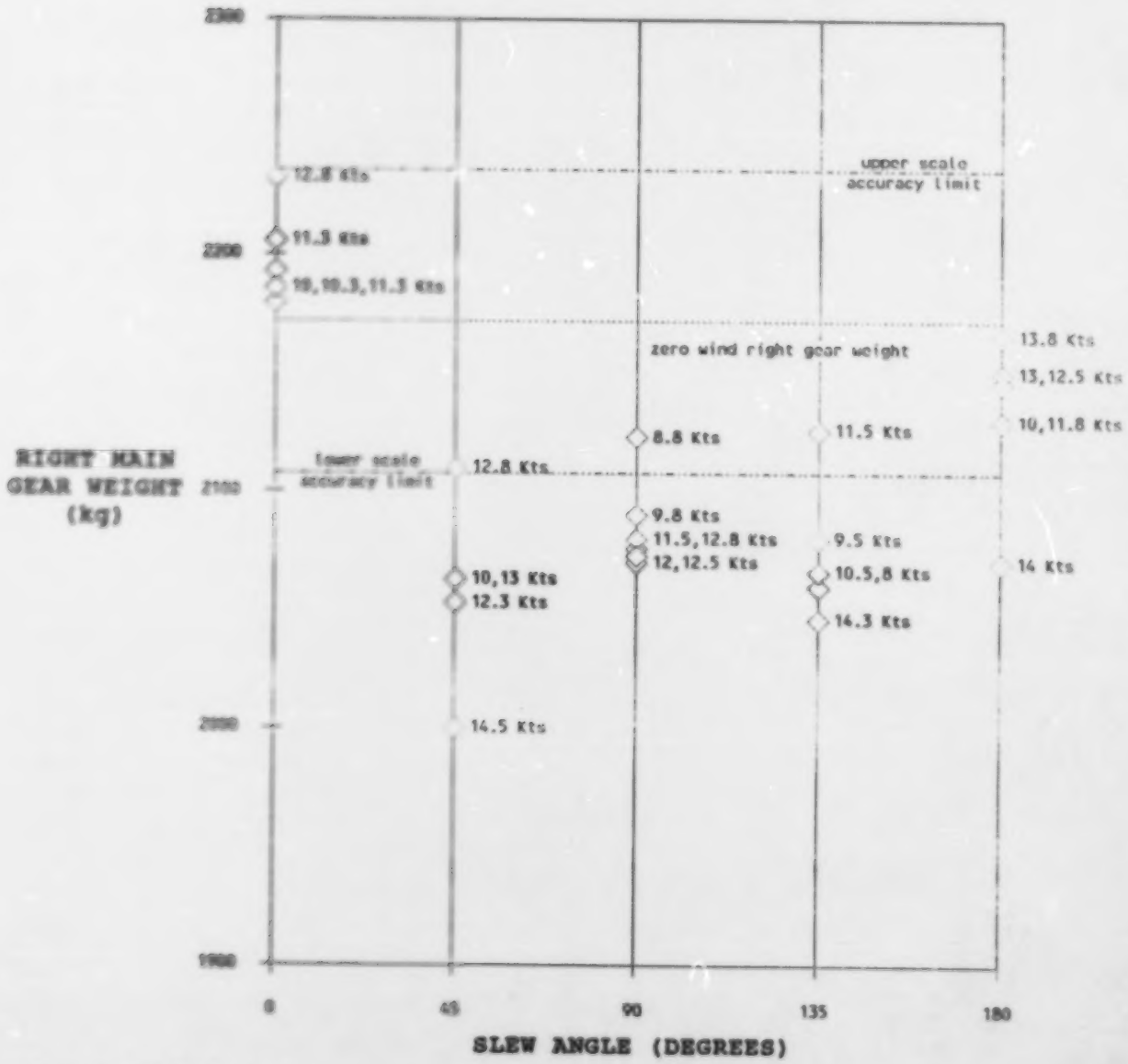
Source: APS Analysis

FIGURE 3.5
NOSE GEAR RECORDED WEIGHT VERSUS SLEW ANGLE (WITH WIND SPEED) - TWIN OTTER



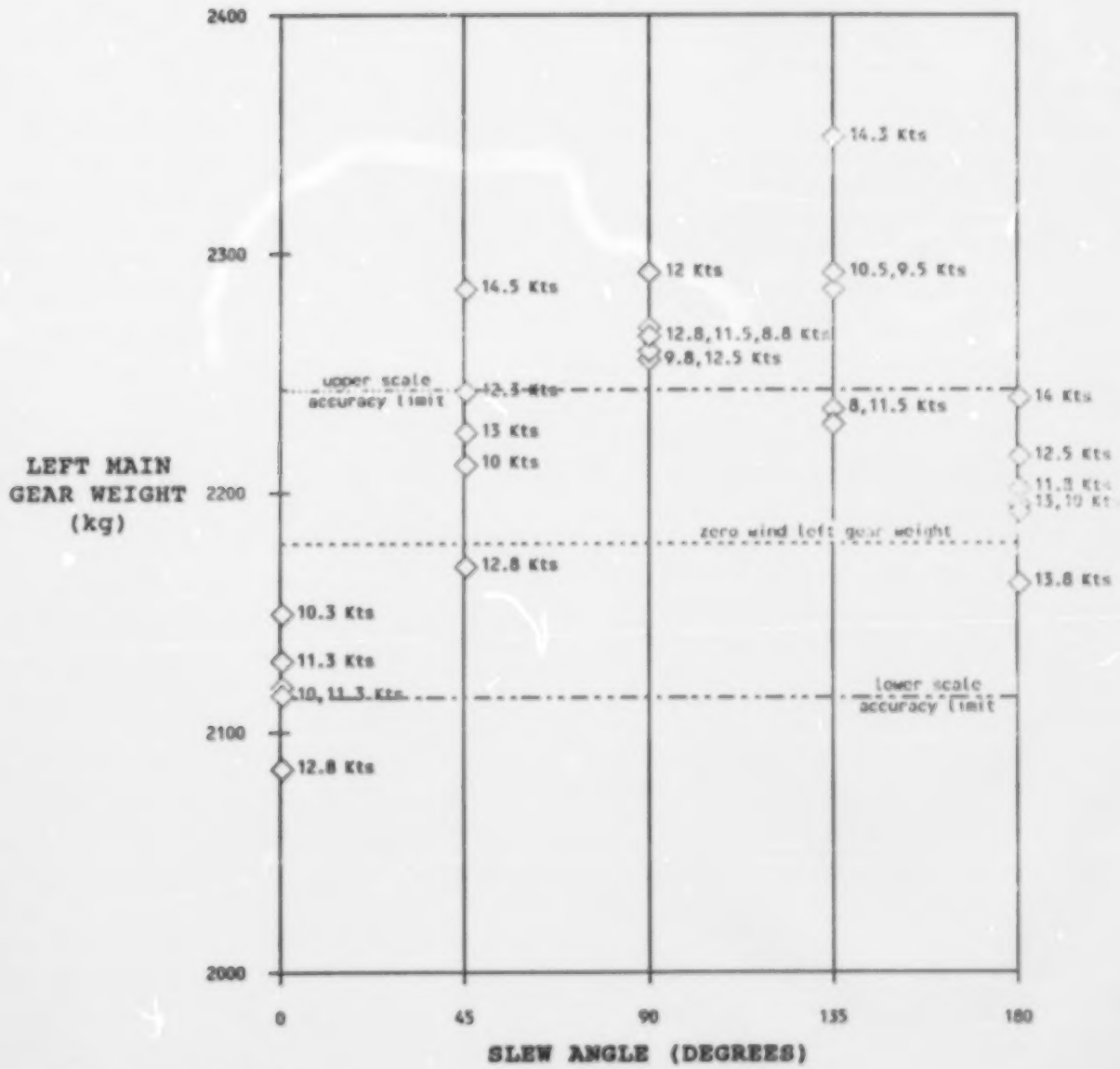
Source: APS Analysis

FIGURE 3.6
RIGHT MAIN GEAR RECORDED WEIGHT VERSUS SLEW ANGLE (WITH WIND SPEED) - TWIN OTTER



Source: APS Analysis

FIGURE 3.7
LEFT MAIN GEAR RECORDED WEIGHT VERSUS SLEW ANGLE (WITH WIND SPEED) - TWIN OTTER



Source: APS Analysis

Some particularly useful experimental observations were:

- The sum of the individual pad readings was, in the majority of cases, less than the benchmark weight of the aircraft (Figure 3.4). Readings with totals above the accepted weight value were only marginally so.

- The nose gear readings (Figure 3.5) were almost always lower than the benchmark value. Note that the nose pad weight at times does not lie within the lower scale accuracy bounds, implying a lower reading than the actual weight.

- The loadings on the left and right gears approximately mirror each other as seen in Figures 3.6 and 3.7. The effect of the wind on these landing gear units exceeds potential scale error in many cases, although the total is within limits. Consequently, the lateral position of the centre of gravity is very affected by the wind.

- Although not indicated directly by the graphs, the longitudinal position of the centre of gravity has been determined to show almost no variation. The benchmark value of the CG is 4.00 m from the nose gear. Wind affected values range from 3.99 m to 4.04 m, which represents a maximum variation of 1 percent. This is a clear indication that, when the aircraft is on the ground, the longitudinal centre of lift is near the longitudinal centre of gravity.

3.5 Wind Tunnel Tests

3.5.1 Aircraft Models and Initial Testing

The consultants were not able to locate a reduced model of the aircraft of interest. However, a plastic, 1/48 scale model kit of a Cessna 150 was found and assembled for wind tunnel studies.

The wind tunnel employed had a test section 33 cm wide by 28 cm high by 48 cm long. The mounting post was 5 cm in diameter. The tunnel and mounting post were calibrated prior to the trials.

The model was mounted on a balance in the wind tunnel and was subjected to direct, 0° slew winds up to about 80 knots, and at 30° slew up to about 9 knots, when the model broke loose from the support.

A second set of wind tunnel tests was performed using a 1/50th scale model of a SOCATA MS 235.

3.5.2 Wind Tunnel Results

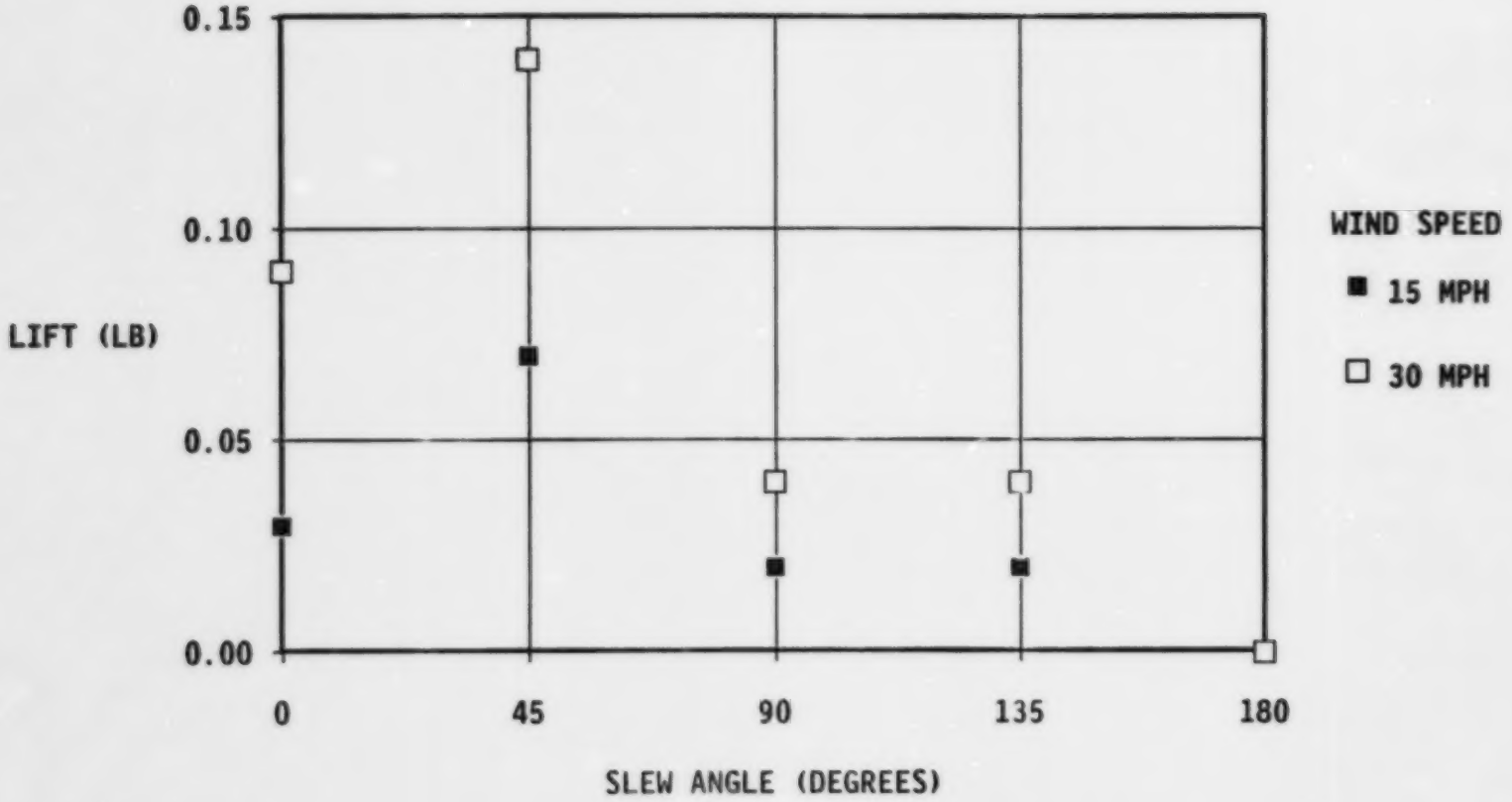
The CESSNA 150 model was fastened securely in the wind tunnel for these tests. The model was subjected to winds up to 48 kph for slew angles ranging from 0° to 180°, in 45° increments. Lift and drag forces were recorded and the effect of the mounting pole was factored out of the results.

The effect of slew angle on lift is visible in Figure 3.8. The data are presented for two wind speeds, 24 kph (13 knots) and 48 kph (26 knots). It must be understood that a 13 knot wind on a model in the wind tunnel does not correspond to a 13 knot wind outside on a real aircraft. The model's size affects the Reynolds number and, hence, the coefficient of lift, C_L. However, the lift and drag profiles will have shapes corresponding to those experienced by the actual aircraft outdoors under similar slew angles.

The pattern visible in Figure 3.8 gives some explanation as to the reason the first wind tunnel aircraft model broke loose from its support. At a 30° slew angle, the lift on the aircraft would be greater than the lift at 0°. If the aircraft had not been securely affixed, it is possible that an incident could occur under these conditions.

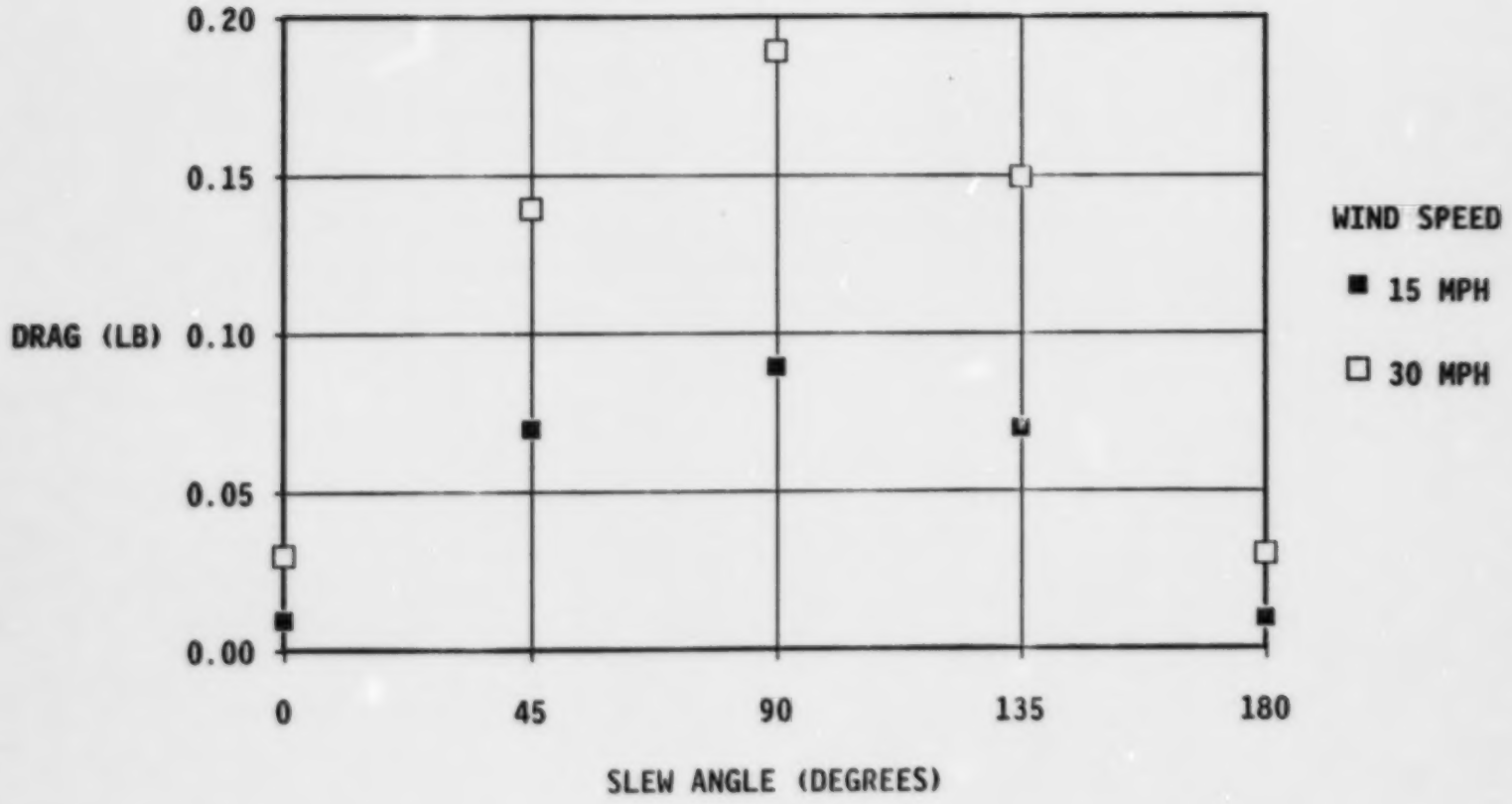
The drag profile is presented in Figure 3.9. It is symmetrical about the 90° slew angle. We can attempt to correlate this drag profile to the drag areas presented in Table 3.2. If the table had been computed in 45 degree increments, instead of in 30 degree increments, the drag area could follow the same pattern as Figure 3.9. This is probable given the fact that the values in Table 3.2 originated from photographs taken from approximate slew angles.

FIGURE 3.8
SOCATA MODEL LIFT vs SLEW ANGLE



Source: APS Analysis

FIGURE 3.9
SOCATA MODEL DRAG vs SLEW ANGLE



Source: APS Analysis

3.6 Modelling Analysis

The model equations given in Section 3.3.1 have been solved using "TK Solver Plus". This software can solve sets of equations. To use the software, sets of equations are entered in their "natural form" and TK solves them automatically, for any conceivable combination of unknowns. A more detailed description of "TK Solver Plus" and a sample problem are provided in Appendix B.

A comprehensive test series for the Twin Otter was undertaken and the analytical results are shown in Table 3.3. The table shows that most results provide lift and drag values that are within reasonable bounds.

Five sets of data are available at 45°. The third has a negative friction coefficient. Given sensitivity of the calculations to the experimental parameters, measurement errors and the restrictive assumptions, the other four are within the error bounds. The lift lies between 75 and 100 kg over a wind range of 10 to 15 knots. Similarly the drag lies between 34 and 87 kg.

Trials run with the wind blowing from behind the aircraft give several values for total aircraft weight which slightly exceed the actual value. These result from negative lift coefficients, suggesting that the aircraft is being "held to the ground" by the wind. This may be because of the pitch of the wing to the wind and/or the effect of the tail surfaces, which were neglected in the analysis. We conclude that measurements should not be undertaken with the wind behind the aircraft.

The calculations are unstable for aircraft pointed directly into the wind and for those with the wind

TABLE 3.3
COMPUTATIONAL MODEL CALCULATIONS
TWIN OTTER FIELD TRIAL INPUT DATA

Fnose (kg)	Fleft (kg)	Fright (kg)	FTotal (kg)	V kt	sigma (°)	dD (m)	dL (m)	dWT (m)	dLT (m)	mu	FLift (kg)	FDrag (kg)	Cd	Cl
537	2,120	2,193	4,850	10	0	4.5	3.8	-0.03	0	0.008	51	39	3.02	1.04
533	2,130	2,206	4,869	12	0	4.5	2.9	-0.03	0	0.010	32	50	3.12	0.52
537	2,116	2,180	4,833	11	0	4.5	4.0	-0.02	0	-0.006 a	68	-29 a	-1.89 a	1.15
537	2,150	2,186	4,873	11	0	4.5	3.3	-0.01	0	-0.007 a	28	-36 a	-2.65 a	0.54
537	2,086	2,233	4,856	13	0	4.5	3.7	-0.06	0	0.013	45	61	2.94	0.57
533	2,213	2,063	4,809	10	45	4.5	3.9	0.06	0	0.017	92	82	6.74	1.97
530	2,243	2,053	4,826	13	45	4.5	3.6	0.07	0	0.018	75	86	4.53	1.03
520	2,286	2,000	4,806	15	45	4.5	3.3	0.11	0	-0.034 b	95	-163 b	-6.38 b	0.97
533	2,226	2,063	4,822	13	45	4.5	3.8	0.06	0	0.010	79	47	2.28	1.00
523	2,170	2,110	4,803	13	45	4.5	3.5	0.02	0	0.017	98	81	3.87	1.21
513	2,256	2,070	4,839	13	90	4.5	2.2	0.07	0	0.027	62	129	6.70	0.84
510	2,256	2,090	4,856	10	90	4.5	1.0	0.06	0	0.017	45	83	6.24	0.89
503	2,260	2,123	4,886	9	90	4.5	-8.0 c	0.05	0	0.026	15	129	12.94	0.39
503	2,270	2,076	4,849	13	90	4.5	0.9	0.08	0	0.028	52	138	6.69	0.66
503	2,266	2,080	4,849	12	90	4.5	0.9	0.07	0	0.029	52	139	8.60	0.84
503	2,293	2,073	4,869	12	90	4.5	-1.3 c	0.09	0	0.011	32	56	3.02	0.45
493	2,236	2,060	4,789	8	135	4.5	2.4	0.07	0	0.033	112	160	20.48	3.75
517	2,350	2,046	4,913	15	135	4.5	14.8	0.12	0	0.020	-12	99	3.88	-0.12 d
513	2,286	2,080	4,879	10	135	4.5	-2.0 c	0.08	0	0.018	22	89	7.15	0.46
513	2,293	2,066	4,872	11	135	4.5	-0.4 c	0.09	0	0.007	29	34	2.45	0.55
530	2,230	2,126	4,886	12	135	4.5	0.1	0.04	0	0.014	15	66	3.78	0.22
547	2,163	2,166	4,876	14	180	4.5	4.9	0.00	0	-0.012 a	25	-58 a	-2.41 a	0.27
543	2,196	2,150	4,889	13	180	4.5	3.9	0.02	0	-0.002 a	12	-11 a	-0.53 a	0.15
547	2,216	2,146	4,909	13	180	4.5	3.1	0.03	0	0.002	-8	9	0.48	-0.11 d
553	2,193	2,130	4,876	10	180	4.5	6.0	0.02	0	-0.002 a	25	-9 a	-0.70 a	0.53
553	2,240	2,070	4,863	14	180	4.5	5.5	0.07	0	0.001	38	6	0.24	0.41
543	2,203	2,130	4,876	12	180	4.5	4.2	0.03	0	0.004	25	20	1.14	0.37

NOTES: (a) Calculated values of drag parameters are very sensitive to transverse positions of centre of drag. At 0° and 180° slew angles, negative values for mu, FDrag, and Cd are due to slight variation in slew angle which reversed the drag vector direction.

(b) Negative mu, FDrag, and Cd at 45° slew angle most probably due to raw data error (note abnormally large spread between Fleft and Fright).

(c) Negative dL indicates that centre of lift is in front of the nose gear. Possible explanations are negative lift on the aircraft tail (resulting in an upward moment about main gear) or data error.

(d) Negative lift coefficient strictly due to input data. Total of the three pads exceeds the nominal weight

Source: APS Analysis

blowing in the opposite direction. This is because aircraft may wobble when directed into the wind, particularly if there are perturbations in wind direction. The reasoning is that if the aircraft is positioned such that its slew angle is, say, 45° then a small perturbation in wind direction (slew angle) will not appreciably change either the magnitudes or directions of any of the forces being measured or calculated. However, if the aircraft is positioned so that it faces directly into the wind, then a slight perturbation in wind direction will not only alter the magnitude of the calculated values (specifically horizontal, or drag forces) but will also change the direction (sign) of those values. The same argument can be used with the case of a 180° slew angle. This phenomenon is visible in Table 3.3. The argument is valid within the limitations of the model. The consultants had no way of measuring the horizontal resistance/load at each pad. Nevertheless, it is exactly this resistance which balances the drag force. The assumption that the friction coefficient, μ, was the same at each gear is a very reasonable one. However, μ may very well not be the same at each pad, but, if so, the consultants have no way of measuring how it differs. This "uncertainty" is passed into the computational model which forces the results to coincide with the input equations and assumptions and may result in confusion surrounding some computed values.

In all other cases, to the limit of the assumptions in the analysis, under all wind conditions, the results seem reasonable.

4. SUMMARY OF RESULTS

The field trials, wind tunnel tests and the computational model have all been used as analytical tools in the study of the effects of wind on the measured weight of an aircraft. It is obviously desirable for the different methods to support one another in their conclusions. This was done in many cases.

For example, the raw data from the field trials was used as input into the computational model to see if the results correspond to the wind tunnel results. By showing that the results from the computational model are, for the most part, very reasonable and in agreement with another independent set of results, we have shown that the models are valid.

The best correlation between tests is found when comparing the field trials to the wind tunnel data. When the total recorded weights of the Twin Otter on Figure 3.4 are examined, it may be considered strange that the weights are lower at a 45° slew angle than at a 0° slew angle. This would imply that the lift on the aircraft is higher at a 45° slew angle than at 0°. The results shown in Figure 3.8 supports this observation entirely. The lift on the aircraft increases as the slew angle increases from 0° before decreasing at some point most probably beyond 45°.

The drag pattern on Figure 3.9 is validated by the values for drag on Table 3.3. From Table 3.3, for all wind speeds, the average calculated magnitudes for drag are 43 kg, 92 kg, 112 kg, 90 kg, and 19 kg for slew angles of 0°, 45°, 90°, 135°, and 180°, respectively. The same symmetrical distribution about the 90° slew angle that appears in Figure 3.9 is apparent in these calculated numbers.

5. CONCLUDING REMARKS AND RECOMMENDATIONS

Aircraft weight may be measured reasonably in winds. However, the results may not be reliable if the winds are directed along the aircraft centre line from behind the aircraft. For winds directly along the longitudinal axis from in front of the aircraft, the net vertical forces (i.e., the lift minus individual pad recorded weights) will be measured accurately while the drag parameters are uncertain.

For wind speeds less than about 10 knots, despite the lift and drag loading, the aircraft total load, as recorded from weigh scales readings falls well within the accuracy limits of the scales. That is, when an aircraft weight is estimated at about 4900 kg and the wind velocity is less than 10 kts, the sum of the weigh scale measurements will provide an approximation of the weight to within 100 kg, i.e., within the accuracy of the scales. Furthermore, this difference is almost exclusively on the low side of the measurement, meaning that the weight being recorded is less than the actual aircraft weight.

Therefore the consultants recommend that if overloaded aircraft are to be successfully identified, aircraft should be weighed such that the angle between the wind direction and the longitudinal centre line ranges from -90 to +90 degrees[2]. Under these conditions, with non-gusty winds below 10 knots, the weights recorded will be, at most, the actual aircraft weight, and more probably below the aircraft weight.

Weights taken with the wind outside the recommended range will usually provide a weight at or below the actual aircraft weight. However, the uncertainty in such a case makes the

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[2] Excluding directly toward the nose due to lateral instability as discussed earlier.

"real" weight an unknown.

Within these recommendations, the possibility remains that a slightly overloaded aircraft will not appear to be so when weighed in the wind. This is of no great concern as marginal cases are rarely of interest. It is certain though, that an aircraft with a measured substantial overload will be overloaded by at least this amount and most probably more.

A mechanism to accurately calculate the actual weight of an aircraft in windy conditions would be ideal. This would take the form of some offset value dependent on wind speed, direction and aircraft type. However, the limited scope of this project makes it impossible for the consultants to recommend such a "correction factor". The very nature of wind creates uncertainty in its measurement. Extremely numerous, highly controlled tests would have to be made to determine a statistically acceptable value. This is unfeasible as the tests would have to be repeated for every type of aircraft.

The approach and analytical method used in this report can also be applied to larger aircraft. Because larger aircraft will have larger wings, the magnitude of the effect due to wind will be greater than that found here, although the scale error, too, will increase. The conclusions discussed in this report should also apply to these aircraft although parameters such as wind speed limits may vary.

PHASE III - OVERLOADED SEAPLANE DETECTION

6. INTRODUCTION

The objective of this phase of the project was to develop and recommend suitable approaches for determining the gross weight of seaplanes and float planes.

6.1 Problem Definition

Unlike conventional land-based planes, seaplanes cannot be loaded onto a set of scales to determine whether the aircraft are overloaded. The problem is, therefore, to define a procedure which an inspector could perform on an aircraft floating in the water to detect potential overloads. This procedure should be based on simple measurements and should not require the installation of permanent devices or marks on the aircraft and/or float structure.

6.2 Methodology

The study methodology followed, in general, the presentation format of this report and is summarized by the following elements:

6.2.1 Conceptual Solution

Conceptualization of a theoretical method of "weight by buoyancy calculation" which could be based on the geometry of a specific type of float.

6.2.2 Float Specifications

Acquisition and analysis of the specifications of a standard float. Data had to be complete, detailed and accurate.

6.2.3 Algorithm and Computer Program

Preparation of an algorithm and program which could accept as input the measured depths of floats in water and return a weight of the aircraft as output.

6.2.4 Field Trials and Model Evaluation

Performance of field tests to validate the above. Field testing would consist of:

- Securing test site (Marina);
- Securing test aircraft;
- Securing equipment to transport float plane from dry land to water and vice-versa;
- Weighing aircraft on dry land;
- Taking depth measurements in water using some suitable method or apparatus;
- Repeating above measurements with different loads on aircraft.

Comparison and analysis of all data obtained. Review or rework of computational method if necessary.

7. CONCEPTUAL SOLUTION

The total weight of a float plane (including floats and any residual water in the hull) is equal to the total buoyancy of the system. Buoyancy can be equated to the weight of the water displaced by the floats (or the airplane shell for seaplanes). Therefore, the weight of the aircraft is directly related to the volume of its submerged parts and to the density of the water[3].

The total buoyancy of the aircraft system is given by:

$$B_t = B_1 + B_2 + \ldots + B_n$$

Where B_t = total system buoyancy
B_i = individual immersed element buoyancy

The individual buoyancies, B_i, are equivalent to the submerged volume of the immersed part multiplied by the density of the water. That is:

$$B_i = V_i * rho$$

Where V_i = individual element submerged volume
rho = density of water

Each partial buoyancy is a vertical force applied to the element's centre of buoyancy, defined as centre of gravity of the submerged portion, with the submerged volume having the same density as the surrounding water.

Therefore, the point of application of the total buoyancy is the point of application of the resultant of a system of

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[3] All tests were done in fresh water. Salt water testing was not feasible within the constraints of this study.

vertical forces, each applied at its corresponding centre of buoyancy. In mathematical terms, each coordinate of the point of application of the total buoyancy, with reference to a generic Cartesian coordinate system, is given by the sum of all first order moments of the individual buoyancies of the physical system, with respect to the other coordinate axis, divided by the system total buoyancy (Ref.1).

With the system in static conditions, the airplane centre of gravity is located on the vertical of the point of application of the system total buoyancy.

The weight of the aircraft and its centre of gravity can therefore be determined through the following steps:

1) measurement of the waterline of each immersed part of the airplane;

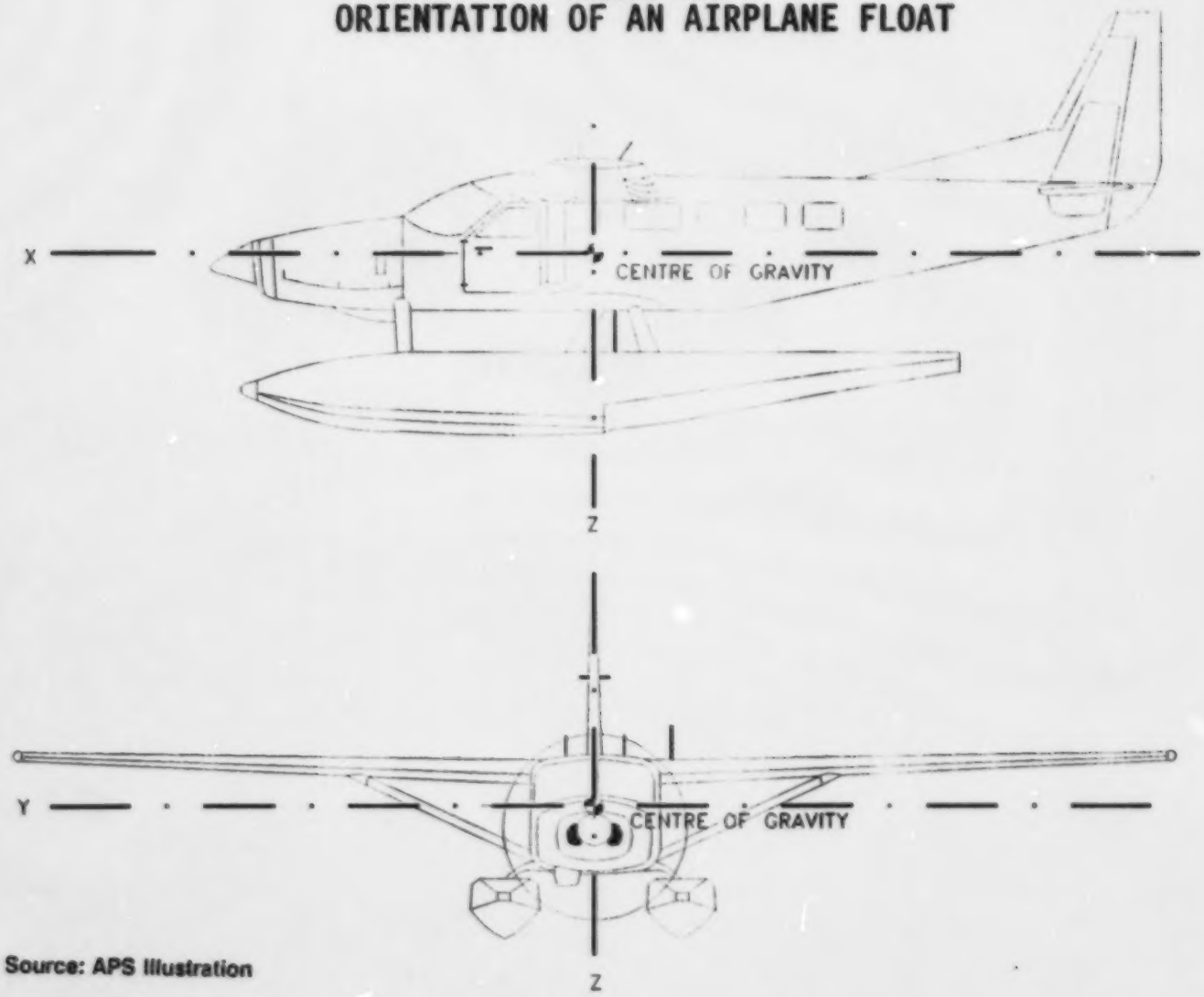
2) calculation of the buoyancy and centre of buoyancy of each immersed part;

3) calculation of buoyancy and centre of buoyancy of the aircraft.

All submerged elements of a float plane or of a seaplane are portions of streamlined bodies symmetrical with respect to a plane parallel to the XZ plane of the conventional airplane body coordinate system as shown in Figure 7.1.

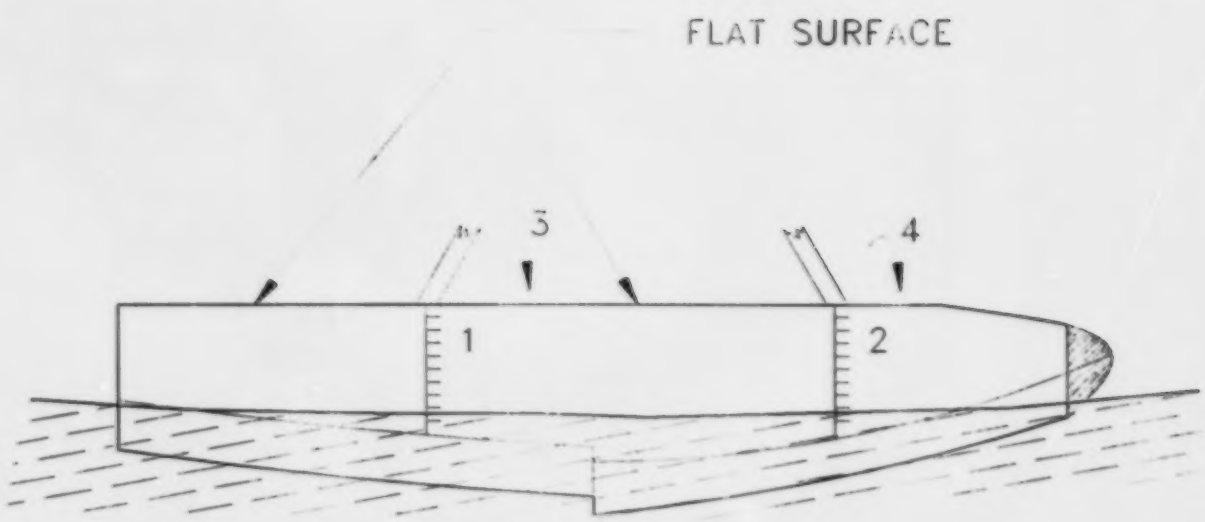
Given this symmetrical relationship, the waterline of any submerged element can be determined by measuring the height of the water level at four fixed points - two per side of the element symmetrically opposed by a pair on the other side of the element. For most standard floats, these measurements can be taken with reference to the flat upper surface of each float as in Figure 7.2.

FIGURE 7.1
ORIENTATION OF AN AIRPLANE FLOAT



Source: APS Illustration

FIGURE 7.2
DETERMINATION OF WATERLINE OF A FLOAT



Source: APS Illustration

In the case of float planes, we are dealing with two floats per aircraft, which would entail a total of eight measurements. However, since the two floats are identical in structure, the number of measurements could be reduced to four - for instance, two on the port (left) side of the left float, and two on the port side of the right float. These four measurements could be read from a dock by using a measuring device attached to a (telescopic) pole. Knowing the geometry of the floats, it would then be possible to obtain equivalent, zero list (i.e., no lateral tilt) waterlines for each float, and then a zero list waterline for an effective single float.

By always working with an equivalent, zero list waterline we can reduce the buoyancy calculation to a calculation of the half-volume submerged portion of the immersed element. The element buoyancy is then twice this half-volume multiplied by the water density. For a float plane, the total buoyancy would be 4 times the equivalent , zero list, half-volume times the density of the water.

In the Marine Industry the buoyancy and centre of buoyancy of a hull is calculated as the resultant of partial buoyancies and centres of buoyancy under various load conditions (Ref 2). The buoyancy of a half float of an airplane or of a half hull of a seaplane can be calculated by numerical approximation, dividing the submerged half-volume in cells having a square one inch side base on the XZ symmetry plane and a Y dimension equal to the distance of its base from the element side (Figure 7.3). The coordinate of the centre of buoyancy can be calculated taking the relevant first order moments of each cell, weighted with the cell Y dimension, summing all of them and dividing the result by the half-volume buoyancy. The centres of buoyancy can be calculated with respect to some local origin or a system origin, as long as the correct geometrical relationships are made.

FIGURE 7.3
BUOYANCY CELLS

BUOYANCY CELL (i,j) WITH LOCAL COORDINATE ORIGIN

Source: APS Illustration

In general, the total buoyancy is the sum of all partial buoyancies of the system. The centre of buoyancy is the point of application of the total buoyancy, with coordinates resulting from the application of first order moments to all the system partial buoyancies and centres of buoyancy.

For an airplane on floats, the total buoyancy is four times the buoyancy of the submerged half-volume of the zero list equivalent float, while the airplane centre of gravity has the same X coordinate of the submerged half-volume.

8. FLOAT SPECIFICATIONS

The method of the previous section was used to calculate the theoretical weight of a float plane. This weight was validated through field tests. Therefore, the float specifications studied came from a float model which was accessible for field testing. The consultants therefore chose float model C-3500 of the PEE KAY Float Division of the De Vore Aviation Corporation.

The consultants were supplied with a float assembly drawing and float installation limitations drawing. These drawings were used to establish all geometrical parameters necessary for analysis.

The total buoyancy of this float is 3,500 lbs. Note that the value is usually indicated in the model number (in this case C-3500).

9. ALGORITHM AND COMPUTER PROGRAM

The principles outlined in Section 7, Conceptual Solution, have been applied to a software package which can determine the weight and centre of gravity of a float plane.

The package (called FLOAT) is set to accept aircraft using floats model C-3500 as presented in Section 8. With minor modifications, the package can accommodate virtually any float on the market. A similar package can be written for seaplanes. Details of the FLOAT program are included in Appendix C.

Once the specific float data has been correctly entered into the program, all that is required are the water levels at both the forward and aft panel points on one side of each float. These water levels are used by the program to determine the total buoyancy (and hence, the weight) of the aircraft. It would therefore be possible for an inspector to obtain the "weight" of an aircraft from a dry position on the dock.

To check the precision of the calculating algorithms we compared the actual float total buoyancy with the algorithms calculated value.

> The total buoyancy of the float model C-3500 was 3,500 lbs.
>
> The total buoyancy of the same float, computed by the software package FLOAT was 3,521 lbs, giving an error of +0.6%.

The algorithm error could be used as an offset for measurements, equivalent to a "TARE" for scales.

10. FIELD TRIALS AND MODEL EVALUATION

Field trails were performed on an airplane equipped with PEE-KAY-C-3500 floats at the Marina Venise in early June, 1990. It should be noted that the field trials were twice cancelled due to inclement whether, as it was required that both the winds and the water be calm for testing.

The aircraft was first weighed on land using 4 pads from the Haenni system. Because of its awkward shape, the aircraft was loaded onto wooden blocks placed on the pads. This is depicted in Plate 10.1. The scale positions were changed and the weights re-measured to get more data points for averaging. It should be noted that, unlike 3 point weighings, 4 point weighings are extremely sensitive to centre of gravity position (consider the wobble of a table with 1 leg shorter than the others). Therefore, while the total weight is being easily and accurately measured, it is substantially more difficult to find the centre of gravity on land.

The aircraft was then transported to the water using a modified fork lift (Plate 10.2). In the water, the four required water line distances were recorded[4], ie. from the top of the float to the water level at the points of interest - fore and aft of the near side on both the port and starboard floats. The aircraft in the water is shown in Plate 10.3. The aircraft was rotated in the water and repeated readings were taken.

Two sets of trials were done. The first used an empty aircraft with only partially filled fuel tanks and the second used the aircraft with a pilot, a passenger and full fuel tanks.

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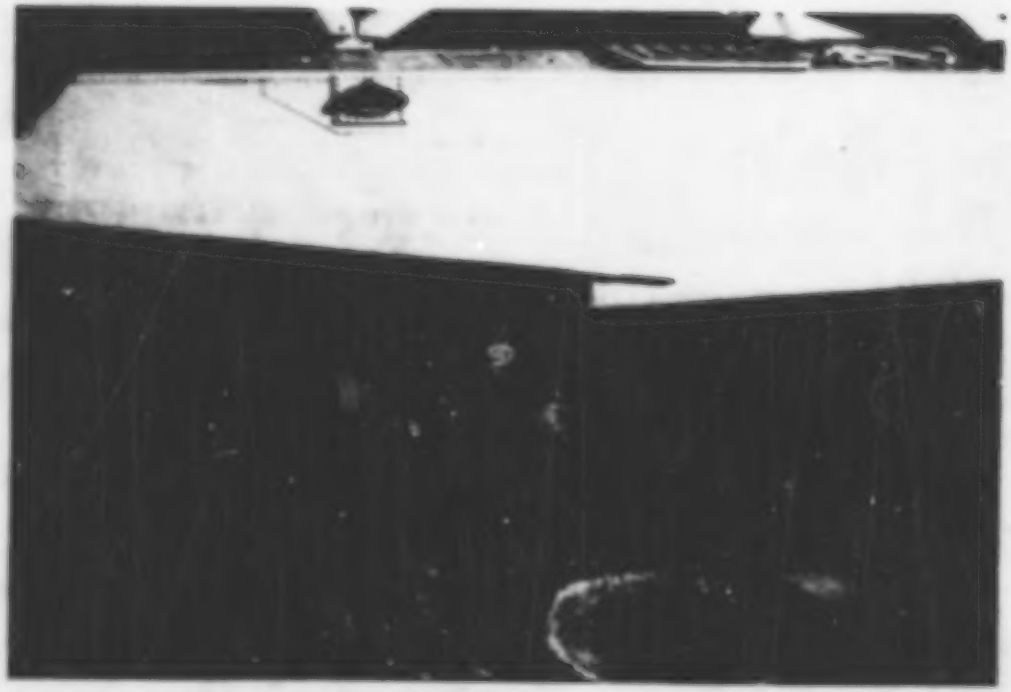
[4] The method of recording "draft" was by counting the number of rivets from the top of the float to the water line. This method was developed on site and proved to be most efficient and simple.

PLATE 10.1
LAND WEIGHT RECORDING OF FLOAT PLANE



Source: APS Photograph

PLATE 10.2
FLOAT PLANE TRANSPORTATION

Source: APS Photograph

TABLE 10.1

FIELD TRIAL RESULTS - RAW DATA

CASE	A: NO PASSENGERS FUEL TANKS DRY					B: 2 PASSENGERS FUEL TANKS FULL				
LOCATION	LAND		WATER			WATER		LAND		
READING	WEIGHT		DEPTH*			DEPTH*		WEIGHT		
UNITS	(Kg)		(IN)			(IN)		(Kg)		
TRIAL	1	2	1	2	3	1	2	1	2	3
LEFT FRONT	190	243	18.5	18.5	19.5	16.4	16.3	283	367	100
LEFT REAR	353	293	14.6	15.0	15.1	12.6	12.6	390	323	577
RIGHT FRONT	57	87	18.9	18.9	18.6	16.1	16.1	127	90	-
RIGHT REAR	473	453	15.1	14.9	14.9	12.5	12.5	547	633	720
TOTAL	1,073	1,076	-	-	-	-	-	1,347	1,413	1,397

*DEPTH MESURED FROM TOP OF FLOAT TO WATER LEVEL

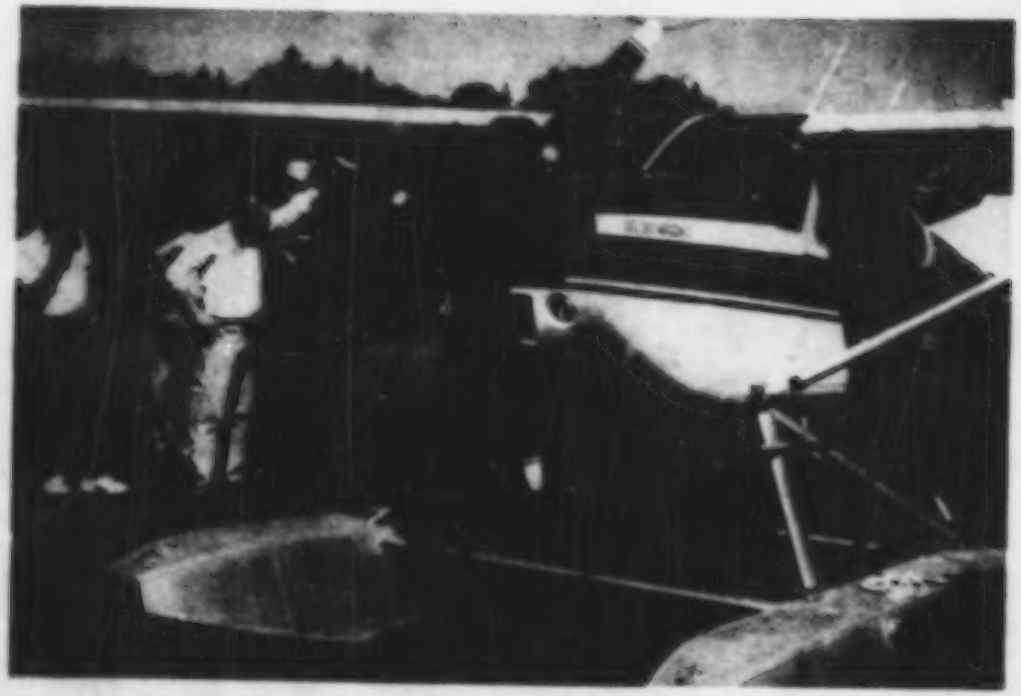
SOURCE: Aviation Planning Services

The raw data from the field trials is presented in Table 10.1. On land, the readings from the individual pads fluctuated as mentioned earlier. The rivet markings were visible to the nearest quarter inch allowing readings to the nearest eighth of an inch. This level of precision was only attainable due to the extremely calm nature of the water. This can be seen in Plate 10.3. Under normal conditions it is not expected that reading precision will be any greater than one half of an inch.

For calculation purposes, the average values of the depth measurements were entered into the FLOAT program and the result was compared with the average land scale reading. These numbers are presented in Table 10.2. The percentage errors are very low (+0.7% for Case A and +3.3% for Case B) before correction. This accuracy may be improved if we account for the fact that the computational model was found to over estimate the buoyancy by +0.6%. The errors are then reduced to +0.1% and +2.7% respectively.

It should be noted that due to the requirement for calm water, (to secure reasonably accurate depth readings) testing in windy conditions was not contemplated. If there were a wind, wave action would render the reading imprecise and undefensible.

PLATE 10.3
FLOAT PLANE IN WATER



Source: APS Photograph

TABLE 10.2

COMPARISON OF MODEL RESULTS WITH RECORDED WEIGHTS

CASE	A: NO PASSENGERS FUEL TANKS DRY				B: 2 PASSENGERS FUEL TANKS FULL		
READING	DEPTH*			AVG. DEPTH*	DEPTH*		AVG. DEPTH*
UNITS	(IN)			(IN)	(IN)		(IN)
TRIAL	1	2	3	-	1	2	-
LEFT FRONT	18.5	18.5	19.0	18.67	16.4	16.3	16.31
LEFT REAR	14.6	15.0	15.1	14.92	12.6	12.6	12.63
RIGHT FRONT	18.9	18.9	18.6	18.79	16.1	16.1	16.13
RIGHT REAR	15.1	14.9	14.9	14.96	12.3	12.5	12.38
AVERAGE TOTAL WEIGHT MESURED	2,366 Lb				3,095 Lbs		
AVERAGE TOTAL WEIGHT COMPUTED	2,383 Lbs				3,196 Lbs		
%DIFFERENCE	0.72%				3.26%		

* DEPTH MEASURED FROM TOP OF FLOAT TO WATER LEVEL

Source: APS Analysis

11. CONCLUSIONS AND RECOMMENDATIONS

This report has shown that it is indeed possible to construct a computer model which could accurately calculate the weight of a float plane or seaplane on the basis of a few simple measurements. The model is float specific, meaning that full and complete specifications are required for each type of float for the model to be operational. This implies the need for a data base of those floats encountered in practice, and a production version of the APS software package incorporating the various float and seaplane types. Compiling the data base of standard floats would be time-consuming but not terribly arduous due to the nature of the model. The software package would require some moderate reworking for it to apply to seaplanes.

The model can also generate a value for the aircraft centre of gravity, something which is very difficult to do accurately, on land, for a float plane.

The method is weather dependent but this is not really a major issue because float planes and seaplanes are normally docked in sheltered areas.

One aspect not discussed in this report is the effect of the environment on the density of the water. Temperature is a non-issue because although there is a dependence of density on temperature, the change is infinitesimal. The other environmental aspect is salt water versus fresh water. The density of salt water is obviously higher than that of fresh water. Although the degree of salination is unlikely to be available, an average salt water density would be all that is required.

Finally, to further the efforts of TCAG, Enforcement, it is recommended that an inventory of the floats and hulls in use

in Canada be prepared. Subsequently, the computer models, of these floats and hubs could be conveniently provided in a tabular or portable PC format for use in the field by the appropriate officers.

REFERENCES

1. Alfred H-S. Ang, Wilson H. Tang "Probability Concepts in Engineering Planning and Design". John Wiley and Son, New York, 1975.

2. Eugene A. Avallone, Theodore Baumeister III, "Mark's Standard Handbook for Mechanical Engineers". McGraw-Hill. New York, 1987.

APPENDICES

APPENDIX A - LIST OF CONTACTS

Dr. M. Sinclair - Head of Flight Research - National Aeronautical Establishment

Dr. B. Wardlaw - Head of Low Speed Aerodynamics Laboratory - National Aeronautical Establishment

Mr. D. Wickens - Aircraft Aerodynamics - National Aeronautical Establishment

APPENDIX B - "TK SOLVER PLUS" SOFTWARE

The equations in this analysis are given in "TK Solver Plus" form in Table B.1. The equations are listed in the "Rule Sheet".

The variables that appear in the equations are listed in the "Variable Sheet" shown in Table B.2. The variable sheet shows six columns: (1) the variable "status", where "L" signals that there is a list of values to be used in the preparation of a table or graph, (2) the input value column for a variable, in the first variable row, the input value is 537 kg, (3) the variable designation, the first one is F1, (4) the output value calculated, (5) the display units for the variable, which may differ from the calculation units, and (6) comments about the variable.

In the example shown, the measured loads at the front gear, right gear and left gear of a TWIN OTTER, are 537, 2120 and 2193 kg, respectively. The maximum error for these measurements are ±32 kg for the nose wheel and ±64 kg for the main gear wheels. Furthermore, the measurements were made in a 9 knot wind blowing at a slew angle of 180° to the longitudinal axis of the aircraft.

The software uses consistent units for calculation, although the display units are provided with appropriate conversions.

Photographs of this aircraft were not available at the time of the analysis, so the actual projected areas for lift and drag are not provided here. Instead, an overall geometric lift and drag area is estimated from published specifications for the TWIN OTTER. The lift and drag coefficients are then "hybrids" which contain the projected areas involved in the calculations.

Based on the measured quantities, we determine that the lift and drag forces are 51 and 35 kg, respectively; the lift and drag coefficients are 1.1 and 2.9, approximately. We point out that the lift coefficient for a NACA 2412 airfoil varies from about -0.4 to

TABLE B.1
MODEL EQUATIONS IN "TK SOLVER PLUS" FORM

RULE SHEET

```
"Force Balance
  Fnose + Fright + Fleft + FLift - W = 0
( Fnose + Fright + Fleft ) * mu - FDrag = 0

"Total load
Fnose + Fright + Fleft = FTotal

"Lift and drag forces
FLift = C*A*V^2/(2*g)
FDrag = CD*Ad*V^2/(2*g)

"Root mean square of wing tip velocities
V=SQRT((V1^2+V2^2)/2)

"Moments around nose gear, normal to aircraft centreline
FDrag*hD - Fright*d2 - Fleft*d2 - FLift*dL + W*dW = 0

"Moments around line through left and right landing gears
Fnose*d2 - W*(d2-dW) + FLift*(d2-dL) + FDrag*hD = 0

"Moments around line through centre of drag, normal to aircraft
    centreline
Fnose*dD - W*(dD-dW) + FLift*(dD-dL) + (Fright-Fleft)*(dD-d2) +
    mu*(Fnose+Fleft+Fright)*hD = 0

"Moment around line through left landing gear, parallel to
    aircraft axis
Fnose*d1 - W*(d1-dWT) + 2*Fright*d1 + FLift*(d1-dLT) = 0

"Moment around line through nose gear, parallel to aircraft
    axis
Fleft*d1 - W*dWT - Fright*d1 - FLift*dLT = 0

"Moment around line through right landing gear, parallel to
    aircraft axis
2*Fleft*d1 + Fnose*d1 - W*(d1+dWT) + FLift*(dLT+d1) = 0

"Moment about vertical axis through nose gear
mu*Fleft*d1 - dDT*FDrag - mu*Fright*d1 = 0

"Moment about vertical axis through left gear
mu*Fnose*d1 + 2*mu*Fright*d1 - FDrag*(d1-dDT) = 0

"Moment about vertical axis through right gear
2*mu*Fleft*d1 + mu*Fnose*d1 - FDrag*(d1+dDT) = 0
```

TABLE B.2
VARIABLE DEFINITIONS AND SAMPLE PROBLEM - "TK SOLVER PLUS"

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
L	937	Fnose		kg	force on front gear
L	2120	Fright		kg	force on right gear
L	2193	Fleft		kg	force on left gear
L		FTotal	4850	kg	load total
	4901	W		kg	weight of aircraft
L	9.5	V1		kts	
L	10.5	V2		kts	
L		V	10.012492	kts	airspeed
L	180	psi		degrees	angle of incident wind
	34.5	Al		m^2	lift area
	0	Ad		m^2	drag area
	1.5	d1		m	half distance between rear gear
	4.5	d2		m	rear gear to front gear
	1.5	hD		m	elevation of centre of drag
L		dD	4.5	m	axial dist - front gear to drag centre
		dL	4.3047204	m	axial dist - front gear to lift centre
	2.995	dW		m	axial dist - front gear to c.g.
L		dWT	.03830035	m	transverse dist - centreline to c.g.
L		dLT	-1.09E-14	m	transverse dist - c/l to centre lift
		dDT	.32059794	m	transverse dist - c/l to centre drag
L		mu	.09723378		friction factor
		A	52.628741		intermediate result
	9.8	g		m/s^2	grav. acceleration
L		FLift	91	kg	lift force
L		FDrag	39.043027	kg	drag force
L		Cl	1.0909983	-	LIFT COEFFICIENT
L		Cd	2.0758026	-	DRAG COEFFICIENT

1.6 at various angles of attack and zero slew angle; the drag coefficient for a square cylinder is about 2.0. The calculated values can therefore be considered realistic.

The location of the centre of lift from the nose gear is calculated as a check. Estimated at 4.4 m from the nose gear, it falls in the region of the wing, as is expected. Likewise, the centre of drag occurs at about 4.5 m from the nose gear.

The "frictional coefficient" μ (mu) is estimated by the calculation at about 0.007. We note that this coefficient must lie between 0 and about 0.4, for the calculation to be physically correct. As defined in Section 3.3.1, the frictional coefficient will be positive when the drag force is positive. However, since the drag force has been defined as a vector (having direction - see Figure 3.2), the possibility of a negative drag force, and hence a negative friction coefficient, exists. Therefore negative values of friction coefficient will appear in the calculations, especially at those slew angles near 0° and 180°, as these are the points where the drag vector reverses direction.

The calculation also estimates the transverse off-set for the weight, lift and drag from the centreline. In this example calculation, the lift is about on the centreline, while the transverse drag is slightly off-centre.

Given the complex geometrical structure of the TWIN OTTER at 180° to the wind and the sensitivity of lift and drag coefficients to the projected areas and the offset of the centre of lift, the calculated coefficients seem to have reasonable magnitudes.

APPENDIX C - "FLOAT" SOFTWARE

The FLOAT software package was written in FORTRAN and is capable of running on any personal computer supporting DOS 3.1 or higher.

The software package FLOAT consists of the following FORTRAN source files:

- FLOAT.FOR
- FLOIN.FOR
- FLOBUO.FOR
- AWEIGHT.FOR
- FLOINI.FOR

The file FLOAT.FOR contains the main program FLOAT that acts as system manager and calls all the required sub-routines in the proper sequence.

The file FLOIN.FOR contains the sub-routine FLOIN that performs the following tasks:

- Reading the float geometrical dimensions;
- Reading the fore and aft panel point distances from the float fore tip;
- Reading the four measured water level distances, taken on the inclined side of the float;
- Computing the vertical components of the water level measurements.

The file FLOBUO.FOR contains the sub-routine FLOBUO that performs the following tasks:

- Dividing the vertical section of the float with respect to its vertical plane of symmetry in a grid of one by one inch cells;

- Computing, for each cell, the distance to the float side;

- Computing, for each cell, the first order moment of its volume with respect to the vertical, starting on the fore tip of the float;

- Computing the total buoyancy of the float by adding all the cell volumes multiplied by the water density;,

- Computing the horizontal distance from the fore tip of the centre of buoyancy, by adding the cell first order moments and dividing by the total buoyancy.

The file AWEIGHT.FOR contains the sub-routine AWEIGHT that performs the following tasks:

- Computing the waterline of the equivalent, zero list, float;

- Selecting the cells under the waterline;

- Computing the total buoyancy and centre of buoyancy of the float submerged part, applying the procedure of sub-routine FLOBUO to the underwater group of cells.

The file FLOINI.FOR is a service file containing all type and common block declarations.

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